35. Surveying

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The Global Positioning System (GPS) became available as a civilian geodetic survey technology in the early 1980s. It has since revolutionized not only geodesy, but surveying operations as well. Global Navigation Systems (GNSSs) are today a fundamental tool for the land, engineering, and hydrographic surveyor. The majority of GNSS survey tasks relate to the determination of high-accuracy coordinates in a well-defined reference frame, typically using differential GNSS positioning techniques based on the analysis of carrier-phase measurements. Carrier-phase-based positioning is capable of distinct *levels* of accuracy – submeter, few decimeters, centimeter, and even subcentimeter – through a combination of special instrumentation, sophisticated software, and unique field operations. The evolution of GNSS from a geodetic surveying technology to a versatile surveying tool has seen precise positioning implemented in real-time, using ever shorter spans of measurements, and even when the user receiver is in motion. Furthermore, new techniques based on precise single-point positioning, as well as wide-area reference receiver networks, are starting to find wider use.

Among the first civilian GPS user communities in the early 1980s were geodetic surveyors, who used the technology to determine the coordinates of ground marks in control networks. Today, around the world, GNSS is unchallenged as the primary technology for geodetic surveying.

Geodetic surveying requires the determination of geodetic coordinate information that is of high accuracy. This implies a level of coordinate accuracy significantly higher than that possible using standard GNSS open services, such as GPS's Standard Positioning Service (Chap. 7) or Galileo's Open Service (Chap. 9), which deliver meter-to-dekameter level single-point positioning accuracy (Chap. 21). In this chapter, the accuracy requirements for surveying and mapping applications will be assumed to be in the range from subcentimeter to the submeter. Such high positioning accuracy requirements have spurred the development of unique observation procedures, measurement technologies, and data analysis methods – all of which are hallmarks of *GNSS surveying*.

High-accuracy GNSS positioning is synonymous with the differential positioning mode [35.1]. The differential GNSS techniques (Sects. 21.5 and 26.1) range from those based on pseudorange measurements to carrier-phase-based positioning which – depending upon the algorithm and operational mode that is used – can deliver accuracies from a few millimeters to several decimeters. New developments in precise point positioning (PPP; Chap. 25) offer an alternate mode of survey receiver operation that does not require a nearby simultaneously operating GNSS reference receiver.

One of the key features of differential GNSS techniques compared to terrestrial geodetic surveying techniques is that intervisibility between pairs of observing GNSS receivers is not necessary. In fact, the distance between GNSS receivers may range from a few kilometers for land or engineering survey applications, to hundreds and even thousands of kilometers in the case of global geodesy applications. Furthermore, the ground marks whose coordinates are to be determined are *static*. In the case of GNSS geodetic surveying great care is taken to build stable monuments upon which the GNSS antennas are mounted – concrete pillars, steel pins, metal tripods, or poles fixed to bedrock or attached to structures. The assumption is that the three-dimensional coordinates are determined once, and then these coordinated ground marks serve as the datum control marks to which all other (lower accuracy) surveys are *connected*. In this way, the datum or reference coordinate system is propagated to all geospatial data observed using any of the standard terrestrial or GNSS-based surveying and mapping techniques.

For many tasks, the geodetic, land, engineering, or hydrographic surveyor does not require coordinate information in *real-time* (RT). GNSS surveys typically have as their raison d'etre the production of a digital map, the computation of the precise coordinates of the GNSS receiver antenna trajectory, or the establishment of a network of coordinated ground control marks. Nevertheless there are GNSS surveying applications where real-time coordinates are required, as in the case of machine automation applications, or for construction set-out tasks, or trajectory determination, or to navigate from one point to another (Chaps. 21 and 30).

It must be emphasized that *GNSS surveying* is actually an extension of *GPS surveying* – a set of precise satellite-based positioning techniques that have evolved over a period of about three decades [35.1–4]. In fact all mathematical concepts, measurement principles, operational procedures, and applications were first developed using GPS technology. With a heritage of geodetic survey applications, the first decade of GPS surveying was characterized by static positioning in which two GPS receivers recorded measurements during an *observation session*, and subsequent data processing generated the baseline vector connecting a ground point of known geodetic coordinate to a point whose coordinate was to be determined [35.2]. Back in the office, the recorded measurements from the pair of simultaneously operating receivers would be processed, one observation session at a time, to compute the single-session baseline vectors. A network of coordinated points observed in this way would be an effective realization of the geodetic datum, which could be used for subsequent survey and mapping tasks.

During the 1990s, a series of developments led to an extraordinary increase in the productivity of GPS:

- GPS surveying was enhanced by developments that offered an increased flexibility due to the short baseline survey mode.
- Rapid GPS positioning techniques, including real-time operations.
- Use of permanent GPS receivers (obviating the need for the surveyor to operate their own reference station receiver).
- High-accuracy (geocentric) geodetic national and regional datums.
- The availability of GPS data products such as those of the *International GNSS Service* (IGS; Chap. 33).

The drive for improvements in the performance of GNSS surveying techniques continues to this day. Key achievements include faster carrier-phase ambiguity resolution (AR; hence shorter observation sessions), more robust positioning (hence fewer erroneous baseline solutions), and lower operational constraints (hence lower field survey costs). These improvements result from several independent developments, such as multi-constellation GNSS (more satellites), more frequencies (more reliable AR, longer baselines), better designed signals (lower multipath), higher quality satellite clock and orbit data products, standardization of data file and transmission formats, permanent reference receiver networks, real-time carrier-phase-based techniques, geoid models (for height determination), and improved GNSS receiver technology.

Such improvements are not only of benefit to the geodetic and surveying community, but also they are facilitating the adoption of carrier-phase-based GNSS techniques into application areas such as machine guidance and automation (including robotics), rapid mapping (using terrestrial, marine and airborne sensors), construction and mining engineering operations, and precise navigation, to name but a few.

In summary, different GNSS positioning modes and data-processing strategies are all designed to account for systematic errors in the GNSS measurements, or contribute supplementary information for observation models, so as to assure a certain level of coordinate accuracy, at the minimum cost and complexity. The following have fundamental influences on the methods of GNSS positioning (Chaps. 21 and 26 and [35.1, 3, 4]):

1. The type of GNSS measurements – *carrier-phase* measurements are used because of their low noise.
2. Whether positioning is determined in an *absolute* sense using only *single-receiver* measurements, or

defining the position of one receiver *relative* to one or more reference receiver – the former implying the coordinate datum is fixed by satellite orbit information (as in the case of single point positioning or PPP); and the latter by the fixed/known coordinates of the reference receiver(s).

3. Whether the coordinated point is *stationary*, or is in *motion* – the former allows for a *stacking* of measurements that increase the solution redundancy (Chap. 22), and hence improve the precision (and, in general, the accuracy) of the estimated parameters; whereas the quality of kinematic positioning is strongly influenced by instantaneous satellite geometry and the magnitude of residual measurement biases or disturbances.
4. Whether the coordinate solution must be generated in *real-time*, or is derived *post-survey* – the former requires more complex instrumentation and additional infrastructure (variety of communication links, generation of real-time augmentation information, data formats, and protocols); whereas coordinate solutions generated in post-survey mode are typically more accurate than those derived in real-time.

This chapter focuses on the precise positioning applications for geodetic, land, engineering, and hydrographic surveying, and is organized as follows. Section 35.1 introduces the fundamental classes of precise positioning techniques used for the various surveying applications, and discusses the characteristics of static and kinematic type positioning, as implemented in real-time or post-processing methods, based on either the relative or point positioning modes. Section 35.2 discusses the first of the GPS applications that used carrier-phase-based relative positioning techniques – geodetic surveying. All other forms of GNSS surveying have been derived from the basic geodetic surveying principles. Land surveying is introduced in Sect. 35.2. Sections 35.3 and 35.4 deal with engineering surveying and hydrographic surveying applications, respectively.

35.1 Precise Positioning Techniques

Civilian users have from the earliest days of GPS availability demanded ever increasing levels of performance, in particular higher accuracy, improved reliability, lower costs, and faster results. This is particularly true of geodesists, surveyors, and engineers, who seek accuracy that is several orders of magnitude higher than that required by other GNSS users. Although it is possible to categorize positioning applications according to a range of criteria, the following considerations are useful: accuracy, time sensitivity of positioning, time-to-coordinate-solution, receiver kinematics, infrastructure requirements, and nature of supplementary model information. Each of these is discussed below.

Accuracy traditionally has been expressed in relative terms, for example, as a ratio of coordinate error (typically expressed as a 95% uncertainty) to distance (between ground marks, or between GNSS receivers when operated in differential mode). The coordinate error then can be expressed in metric or distance units by scaling the ratio by receiver or ground mark separation. Hence *one part-per-million* (or 1 ppm) is a relative accuracy measure of one centimeter between two points separated by 10 km, or 0.5 cm over 5 km, or 10 cm over 100 km, etc. Furthermore, it can refer to a single coordinate component (e.g., x, y, or z Cartesian coordinates, or the *height component*) or a transformed coordinate quantity such as the *horizontal component*.

Surveys (and hence coordinates derived from them) were (and still are to a major extent) categorized in a *hierarchical* sense, from the highest *geodetic* categories through to lower accuracy control, engineering, and mapping surveys. Nowadays, the range of accuracies for high-accuracy GNSS surveys would be from subcentimeter to perhaps the decimeter-level. There is a complex relationship between, on the one hand, accuracy sought, and on the other hand the GNSS hardware, field procedures, and data-processing strategies that should be used. Some are formulated as recommended standards and guidelines; however many are not. Interestingly, the GNSS hardware varies the least, as invariably multi-frequency GNSS equipment is used no matter what type of survey is conducted (although there are different receiver/antenna form factors). In contrast, the measurement modeling used within the data-processing software varies considerably from commercial systems designed to satisfy the needs of land and engineering surveyors, optimized for rapid and easy use in constrained conditions (primarily with regards to length of observation time and inter-receiver distance), and geodetic software capable of ultra-high-accuracy intended for crustal motion and geoscientific applications (Chaps. 36 and 37).

Timeliness is a critical concern for some engineering and machine guidance applications, where the coordinate results are required without delay. This gives rise to one of the most important distinguishing characteristics of high-accuracy GNSS: real-time operations or post-survey processing. The former has a considerable impact on operations and supporting infrastructure, whereas the latter is sufficient for geodetic applications, land and surveying, and most mapping needs. *Time-to-solution* is closely related to timeliness. Static geodetic survey operations typically require lengthy *observation sessions*; whereas high productivity and RT surveys must have very short *initialization* periods that subsequently enable precise single-epoch positioning. Long observation sessions are necessary for high-accuracy surveys over extended inter-receiver distances (hundreds to thousands of kilometers) typical of geodetic surveying applications. Hence time-to-solution is also closely related to the competitiveness of GNSS with conventional terrestrial surveying technology operating over typical survey project distances of the order of a few tens of kilometers or less.

Kinematics refers to the movement of the GNSS receiver while conducting the positioning task. A GNSS receiver may be in continuous motion, mounted on a variety of land, marine, air, and spaceborne platforms; or attached to a monumented ground mark; or perhaps in hybrid static–kinematic mode. The kinematic survey mode implies single-epoch, single-receiver positioning for each space point on a trajectory. On the other hand, static positioning (especially in post-processed mode) benefits from a massive increase in redundancy in positioning models [35.2] because many measurements can be used to determine the coordinates of a single stationary ground point. However, high-accuracy kinematic positioning capability is critical for many engineering surveying applications (Sect. 35.3).

High-productivity techniques for rapid surveying and real-time operations (e.g., in support of machine guidance, engineering, and construction) are very demanding of *reference receiver infrastructure*, including information technology and wireless communications. Relative positioning requires the operation of one or more *nearby* simultaneously operating reference receivers; whereas techniques such as PPP do not, in general, have this requirement. Furthermore, the density of *reference receiver networks* may vary from very low in the case of the most sophisticated geodetic static techniques or PPP to very high density (typically less than a few tens of kilometers spacing) for high productivity surveys and real-time operations.

Augmentation information is required by all precise positioning techniques, ranging from GNSS measurements at reference receivers in the case of relative positioning techniques to precise orbits, clocks, and perhaps atmospheric/bias information for PPP techniques. With respect to supplementary model information, the critical distinction is between the transmission of augmentation information to users (with all the demands that places on infrastructure operations and service providers) and the provision of such information post-survey impacting upon the timeliness of precise positioning.

In the following sections, the major precise positioning techniques and their distinguishing characteristics are discussed in further detail. It must be emphasized that the development of multi-constellation GNSS receivers, and associated data-processing software, to take advantage of the massive increase in the number of available GNSS signals over the coming years (Chaps. 7–11), will lead to significant improvements in performance – from a reduction in observation session lengths for rapid-static surveys, to single-epoch AR, to relaxed (i. e., longer) user-reference receiver distance specifications (and hence lower infrastructure requirements), to increased reliability and quality of positioning. Furthermore, the increase in variety, access, accuracy, and applicability, and the decrease in latency of GNSS services will also lower the constraints for precise GNSS positioning. However, whether the cost of top-of-the-line geodetic-grade GNSS receivers will fall substantially is uncertain.

35.1.1 Static Positioning

With a heritage of geodetic survey applications, the first decade of GPS surveying was characterized by *static positioning*. The employed techniques can nowadays be generalized to static GNSS positioning and are summarized in Table 35.1. A survey with a minimum configuration of a pair of GNSS receivers progresses as follows [35.1]:

1. One (or more) receiver antenna would be set up on a monumented control point with known datum coordinates (the so-called *reference station* or *base station*), the other(s) over ground mark(s) whose coordinates are to be determined.
2. During an observation session, sufficient measurements of carrier-phase observations to the visible GNSS satellites would be recorded simultaneously by all receivers for a period ranging from an hour (or so) to several days.
3. One (or more) receiver would then be moved to another point and the antenna set up over a new ground mark. The other (or several) reference receiver(s) would occupy the same (or a new) datum control mark(s), and another observation session would ensure that measurements were recorded by the simultaneously operating receivers.

Table 35.1 Summary of precise GNSS positioning techniques – static positioning

- Typical scenario: two or more receivers used simultaneously in campaign, multisession mode, to record measurement files at many points
- Reference receiver separations are project-specific, ranging from tens to hundreds, and even thousands kilometers
- Observation session lengths from about an hour to several days; or continuous observations in case of permanent control or deformation monitoring points
- Monumentation: from highly stable to temporary ground marks
- Top-of-the-line GNSS receivers (carrier-phase measurements on at least two frequencies to form ionosphere-free observables), choke-ring (or equivalent) antennas
- Application typically for the establishment of geodetic control points, or densification of existing control marks
- Commercial software processing is in single-baseline mode, with simplified functional model of estimable parameters consisting of baseline (vector) components and double-differenced ambiguities (unresolved); requiring subsequent single-network adjustment of multiple baseline vectors
- Scientific (geodetic) software has rigorous multi-receiver, multi-session analysis capability; with options to estimate a wide variety of additional orbit, clock, bias, atmospheric, and reference frame parameters
- Resolution of ambiguities is not generally necessary
- Post-processed baselines or multi-receiver scenarios; with datum constrained by reference receiver coordinates; quality is a complex function of many environmental and observation factors, and the degree of sophistication of observation and reference frame modeling

Table 35.2 Comparison of static GNSS positioning techniques

	Single-baseline static GNSS surveying	**Multi-station GNSS geodetic surveying**
Datum	● Base station per baseline processing ● Datum station(s) in network adjustment of baselines	● Small number of reference stations ● Typically IGS stations; International Terrestrial Reference Frame (ITRF)
Inter-receiver distances	● Tens of kilometers	● 100–1000s km
Observation session	● One to several hours	● Several hours to several days
Accuracy	● Relative accuracy of 0.5–1 ppm horizontal, 1–2 ppm vertical; implying centimeter-level coordinate accuracy over typical baseline lengths	● 1–10 ppb; implying centimeter-level coordinate accuracy within GNSS networks over 100–1000s km extents
GNSS hardware	● Single-frequency GPS; or multi-GNSS, multi-frequency receiver ● Light-weight antenna, mounted on tripod	● Multi-GNSS, multifrequency receiver ● Choke-ring (or equivalent) antenna, mounted on stable monumentation
Processing	● Commercial off-the-shelf baseline processing software; automatic processing ● Receiver INdependent EXchange (format) (RINEX) or proprietary data files ● Simplified functional model	● Multi-receiver, multi-station scientific software; considerable analyst skill ● Web processing (automatic) ● RINEX data and auxiliary model or information files ● Sophisticated functional model
Estimated parameters	● Baseline vector ● Double-differenced, unresolved (real-valued) ambiguities ● Following network adjustment: individual receiver coordinates	● Receiver coordinates ● Ambiguities, tropospheric parameters ● Optionally satellite orbits, biases, Earth orientation parameters, etc.
Applications	● Project control surveys; and other postprocessed surveys ● Alternative to terrestrial control survey technologies	● Reference frame observations ● Geodynamics and other geodetic applications

4. This procedure of moving receivers to predefined points, and recording measurements made at all GNSS receivers, would be repeated until all ground marks in the survey area were visited at least once – always ensuring that there was a *link*, or baseline connection, back to one or more datum control points.

There are two classes of static GNSS relative positioning techniques, which are compared in Table 35.2.

On the one hand there are the ultra-accurate, long baseline GNSS techniques – capable of relative positioning accuracies of tenths of ppm up to several parts-per-billion (ppb) over baseline lengths of hundreds to thousands of kilometers. The measurements are made by top-of-the-line, multi-frequency, multi-constellation GNSS receivers and the observation sessions last for many hours or even days. The measurement processing is undertaken using sophisticated scientific software executed in post-survey mode to support a series of global or national geodesy applications (Chaps. 36–39). As an alternative to processing the measurement data themselves – a task that requires considerable analyst skill – surveyors can submit observation data files in the Receiver Independent Exchange (RINEX) format (Annex A.1.2; [35.5]) to one of several web processing engines such as NGS's OPUS [35.6], NRCAN's CRCS-PPP [35.7], GA's AUSPOS [35.8], and others.

At the other end of the spectrum are the medium-to-short baseline GNSS survey techniques. They are capable of accuracies of a few ppm for baselines perhaps up to several tens of kilometers in length and are typically employed to support control network applications. Although low-cost single-frequency hardware could, in principle, be used, today's GNSS surveying hardware is essentially the same *geodetic-grade* receivers as would be used for any of the multi-frequency precise positioning techniques [35.2]. However, the measurement processing is carried out using commercial software packages provided by GNSS receiver manufacturers, distinguished from the scientific software referred to earlier by the use of significantly simplified GNSS observation modeling. In such scenarios the recorded measurements from a pair of simultaneously operating receivers would be processed, one observation session at a time, to compute single-session *baseline* vectors. Following baseline processing, carried out for baselines during each independent observation session, the multiple computed baselines would undergo a *secondary network adjustment* [35.3, 4]. The three-dimensional (3-D) baseline vectors are in effect treated as the observations to be adjusted – with the output being the optimal coordinates of the entire ground control network constrained by datum control points. Such a network of coordinated points can be used for subsequent survey and mapping tasks (Fig. 35.1).

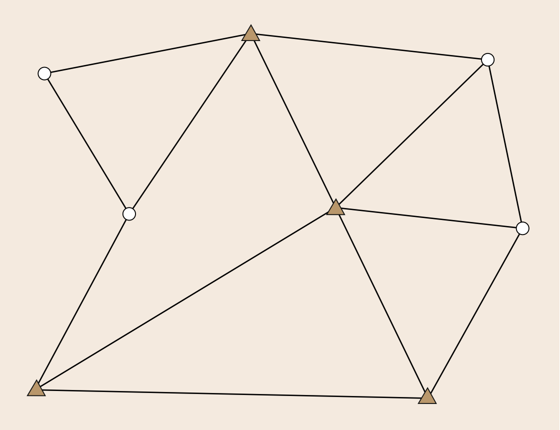

Fig. 35.1 From independent GNSS baselines to survey network: a network of coordinated points is constructed by linking together separate baselines (i. e., pairs of simultaneously operating GNSS receivers) that connect and propagate the known coordinates of ground control marks (*triangles*) to other points whose coordinates are to be determined (*circles*). Each baseline links a GNSS receiver at a point of known coordinates (available a priori or estimated from a GNSS baseline solution) and a receiver whose coordinates are to be determined. Extra baselines can provide redundant pathways of generating coordinate information for quality control purposes

Conventional static GNSS positioning techniques are characterized by long observation sessions. Although an effective means of mitigating residual systematic biases, multipath, and model errors, this imposes significant constraints for routine surveying applications. Over the last two decades several precise GNSS surveying techniques and methodologies have been developed with the following *liberating* characteristics: (a) static antenna setups not required, (b) long observation sessions not essential, and (c) coordinates could be determined in the field. Each is a technological solution to the challenge of ensuring high productivity (coordinating as many points in as short a field survey time as possible) and/or versatility (e.g., the ability to obtain results even while the receiver is in motion and/or in real-time) without sacrificing coordinate accuracy and solution reliability.

35.1.2 Rapid-Static Positioning

For *rapid-static* positioning (Table 35.3) observation session lengths are significantly shorter than for conventional static GNSS surveying discussed above. Ob-

Table 35.3 Summary of precise GNSS positioning techniques – rapid-static positioning

- Typical scenario: one user receiver in single-baseline configuration
- Reference receiver may be operated by user or by third party, on a single project basis or as continually operated reference receiver; datum defined by reference receiver coordinates
- User-reference receiver separations typically tens of kilometers, often $< 10\,\text{km}$ for very fast surveys
- Observation session lengths from a few minutes to over 30 mins, but must be sufficient for ambiguities to be resolved
- Monumentation standards are project specific
- Multi-frequency GNSS receivers (carrier-phase and pseudorange measurements), light-weight (portable) antennas
- Applications are typically the coordination of many ground marks, minor control, detail, or as-built surveys
- Data processing via commercial software; may also be undertaken in real-time mode
- Relatively fast high-accuracy GNSS surveying tool
- Assuming use of multi-frequency receiver, quality of solution is a function of baseline length (degree of cancellation of spatially correlated biases), observation session length, quality of measurements, number of tracked satellites, sophistication of data-processing algorithm

servation session length is a complex function of user-reference receiver baseline length, number of multi-frequency measurements, number of satellites tracked, satellite geometry, and presence of multipath disturbances. Accordingly, hard and fast rules are impossible to formulate. Typically, however, receivers need only to occupy a station for a period of perhaps a few minutes for baselines of less than 10 km in length and good satellite coverage. Here, *good* refers to the overall number of tracked satellites (a minimum of six is generally sufficient) and their distribution across the sky (i. e., satellites should be observed in at least three of the four NE-SE-SW-NW quadrants). Extended observation sessions of perhaps up to 15 min or more may be required for longer baselines, less tracked satellites, and/or poor sky distribution of satellites. Several references to GNSS survey guidelines with recommendations regarding observation session length are provided in Sect. 35.2.2. When utilizing measurements from the full complement of GNSS constellations, on two or more signal frequencies, it is expected that the length of the observation session will reduce dramatically, perhaps even down to a single-epoch.

The basis of the rapid-static positioning technique is the ability of the measurement-processing software to resolve the ambiguities using a *very short observation session* – the data analysis software must therefore have a *rapid* AR capability (Chap. 23). The rapid-static field procedures are similar to those for conventional static GNSS surveying, except that: (a) observation session lengths are *shorter*, (b) the baselines are comparatively *short*, (c) the satellite geometry needs to be *favorable*, and (d) signal disturbances such as multipath should be *minimal*. While the observation of independent baselines is the same survey scenario as in the case of conventional static GNSS positioning using commercial software, another more common scenario is the determination of *radiations* of vectors from a single (or two or three) reference stations as indicated in Fig. 35.2.

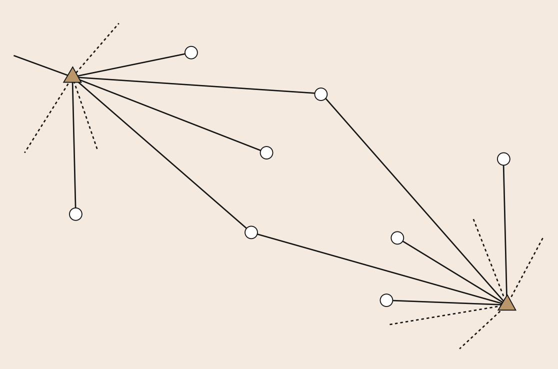

Fig. 35.2 Geometry of rapid-static baselines: static ground points (*circles*) can be coordinated by the differential GNSS positioning mode via the measurement of 3-D baselines connected to base stations with known coordinates (*triangles*). One can see how logistically efficient this method of observing *radiating* baselines is when a GNSS receiver only needs to occupy the ground marks for short measurement sessions. Note the use of two base stations increases opportunities for quality control. Multiple base stations may or may not be operated simultaneously

The rapid-static technique is well suited for short-range applications such as establishing project-scale control and for certain types of land surveys (Sect. 35.2.3). The essential characteristics of rapid-static GNSS positioning are summarized in Table 35.4.

35.1.3 Kinematic Positioning

Table 35.5 lists some of the characteristics of *kinematic GNSS positioning*. We may distinguish between two forms of kinematic positioning. The first is when the coordinates of the moving GNSS receiver antenna's

Table 35.4 Characteristics of rapid-static and conventional static GNSS positioning

	Rapid-static GNSS surveying	Conventional static GNSS surveying
Datum	● Single base station ● Radiation of baseline vectors from single reference receiver	● Base station per baseline processing ● Datum station(s) in network adjustment of baselines
Inter-receiver distances	● Typically less than conventional static	● Tens of km
Observation session	● Few minutes to < 1 h; see *factors impacting on accuracy*	● One to several hours
Accuracy	● 1–2 cm horizontal, 2–3 cm vertical; over typical baseline lengths	● 0.5–1 parts-per-million (ppm) horizontal, 1–2 ppm vertical; i. e., centimeter-level accuracy over typical baseline lengths
GNSS hardware	● Multi-GNSS, multi-frequency receiver (preferred) ● Light-weight antenna, mounted on tripod	● Single-frequency GPS (lower performance); or multi-frequency receiver (preferred) ● Light-weight antenna, mounted on tripod
GNSS software	● Commercial off-the-shelf baseline processing software; automatic processing ● RINEX or proprietary data files ● Simplified functional model; *rapid AR capability*	● Commercial off-the-shelf baseline processing software; automatic processing ● RINEX or proprietary data files ● Simplified functional model
Estimated parameters	● Baseline vector ● Resolved ambiguities, i. e., ambiguity-fixed baseline solutions ● Quality control implemented via re-visit of ground marks	● Baseline vector ● Double-differenced, real-valued ambiguities ● Following network adjustment: individual receiver coordinates
Factors impacting on accuracy	● Baseline length ● Observation session length ● Quality of carrier-phase and pseudorange measurements ● Multi-frequency measurements ● Number of tracked satellites and geometry	● Baseline length ● Observation session length ● Quality of carrier-phase measurements
Applications	● Project control surveys ● Detail, as-built, and other post-processed surveys ● Alternative to terrestrial survey technology	● Project control surveys; and other post-processed surveys ● Alternative to terrestrial control survey technology

Table 35.5 Summary of precise GNSS positioning techniques – kinematic positioning

- Typical scenario: one mobile user receiver in single-baseline configuration; on a variety of land, marine, aerial, or spaceborne platforms
- Reference receiver may be operated by user or by third party, on a single project basis or as continually operated reference receiver; datum defined by reference receiver coordinates
- As with rapid-static surveys, user-reference receiver separations typically tens of kilometers, often < 10 km to ensure AR using geodetic-grade GNSS receivers with short observation sessions
- Single-epoch positioning using double-differenced *carrier-range* observable (double-differenced carrier phase with integer resolved ambiguities), also known as ambiguity-fixed solutions
- Options for re-initialization must be available if signal loss-of-lock on five or more satellites, and may include remaining stationary until ambiguities resolved again, return to previously surveyed static point, etc.
- Multi-frequency GNSS receivers, light-weight (portable) antennas
- Applications typically are the coordination of receiver antenna trajectories, for example, for mapping projects (road centerline surveys, aerial imaging/scanning), satellite orbit determination, hydrographic charting, etc.
- Model and data processing via commercial software; may also be undertaken in real-time mode (see below)
- Assuming multi-frequency user receiver, quality of solution is a function of baseline length (magnitude of residual differential biases), correctness of AR process, quality of measurements (i. e., multipath-free), number of tracked satellites, satellite-receiver geometry (i. e., Dilution of Precision measures)

Fig. 35.3 Precise kinematic GNSS survey: the receiver is installed on a quad-bike with the antenna mounted upon on a pole, and the kinematic positioning task consists of determining coordinates of the antenna on a continuously sampled basis (e.g., once per second) as the bike as driven up and down the beach, to determine a dense network of heights with centimeter-level accuracy for beach erosion studies; note that the antenna height must be corrected for the fixed height of the top of the pole above the ground level (courtesy of Brad Morris)

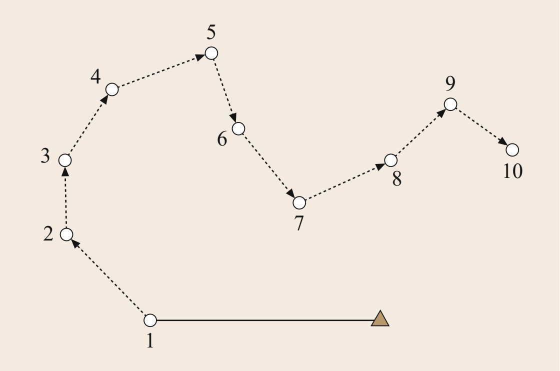

Fig. 35.4 Progress of a *stop-&-go* GNSS survey: the first baseline is observed (known control mark to point 1), and once the ambiguities have been resolved (e.g., using the rapid-static positioning technique), the user receiver's antenna is then moved carefully from point 1 to point 2, then to point 3, and so on, making just a few seconds of measurements while stationary at the ground point (*circle*). Note the base station (*triangle*) operates continuously and the point coordinates are determined by the radiated baseline method (Fig. 35.2); the trajectory of the antenna is not of interest, only the coordinates of the stationary points 1–2–3–4...

trajectory is required (as in Fig. 35.3). The second category is a form of static positioning, but with the special case that the receiver continues to track satellites while it is moved from one static point to another.

The *stop-&-go* GNSS surveying technique deserves special consideration because the coordinates of the receiver are only of interest when it is stationary (the *stop* part); however the receiver continues to function while it is being moved (the *go* part) from one stationary setup to the next, as is indicated in Fig. 35.4.

The first step that needs to be performed in the survey is the initial AR in order that all subsequent single-epoch solutions are based on carrier-range positioning (Sects. 23.2 and 26.3). This technique is well suited to projects where many points close together have to be surveyed, and the terrain does not cause significant signal obstructions.

Instead of only coordinating the stationary points and disregarding the trajectory of the roving antenna, the objective of *kinematic* surveying is to determine the position of the antenna while it is in motion. In many other respects the technique is similar to the *stop-&-go* positioning technique. That is, the ambiguities must be resolved *before* starting the survey, and the ambiguities must be re-initialized *during* the survey when loss-of-signal-lock occurs which causes the ambiguity parameters to change from their initial values. Kinematic positioning invariably involves the determination of vectors radiating from a single (or small number of) base or reference station(s) (Fig. 35.2). Kinematic GNSS surveying techniques are appropriate for road centerline, topographic and hydrographic surveys, airborne applications, etc.

35.1.4 Real-Time Differential GNSS Positioning

Real-time kinematic (RTK) GNSS is a popular technique for many survey applications as there is no post-processing of GNSS measurement data (Sect. 26.3). The standard differential positioning scenario as before requires the use of a pair of GNSS receivers connected by a wireless data link (Table 35.6). Successful operation of RTK-GNSS systems using radio modem data links is typically limited to baseline lengths of 5–10 km due to radio range constraints. Wireless links over the mobile Internet do not have such distance restrictions. However, the inter-receiver distance over which *rapid* AR algorithms work reliably using dual-frequency GNSS instrumentation (with good sky visibility) may only be 20–30 km, and often less in the event of high ionospheric activity (Chap. 39). As with carrier-phase-based kinematic positioning in general, when signals are obstructed the AR algorithm has to be restarted in order to resolve the (new) ambiguity parameters. As this may take several tens of seconds, and if signal interruptions occur frequently, then this

Table 35.6 Summary of precise GNSS positioning techniques – real-time differential positioning

- Rapid-static and kinematic may be conducted in real-time, and collectively these ambiguity-fixed, short-baseline approaches are known as *real-time kinematic* (RTK) techniques
- Operational constraints, reference receiver infrastructure requirements, and GNSS receiver specifications are as for rapid-static and kinematic GNSS surveys (see above)
- May distinguish between operational constraints for *single-base RTK* (with baseline lengths of a few tens of kilometers), and multiple reference receiver *network-RTK* with sparser reference receiver network surrounding user receiver (50–100 km spacing) [35.9]
- Additional infrastructure: networked reference receivers, analysis or network operations facility, and communications links (between reference receivers, and between reference receiver, or RTK service facility, and user receiver)
- Variety of wireless communication links, though increasingly via mobile Internet (terrestrial or satellite) channels; with interoperability afforded by use of industry standard data transmission messages and protocols such as Radio Technical Commission for Maritime Services (RTCM)
- Applications include all those that require precise coordinates in real time, to guide a machine or vehicle, for engineering or construction, and others
- Versatile high-accuracy GNSS positioning technique when supported by the necessary augmentation infrastructure
- Factors impacting quality are as for kinematic surveys, and in addition the reliability of the RTK communications link

dead time can result in RTK-GNSS being a comparatively inefficient positioning technique. The advantage over post-processed implementations of precise kinematic positioning is that when operated in real-time, the GNSS controller is able to alert the user in the event of the need for ambiguity re-initialization (i. e., new AR), or if there is an interruption in wireless communications from the reference receiver or RTK services center.

Most users subscribe to RTK-GNSS services rather than running their own reference receiver. Real-time networks of continuously operating reference stations (CORSs) have been established since the mid-1990s, and there are few signs of this trend slowing. One of the drivers for CORS investment, and the promotion of the use of RTK-GNSS, is the adoption of industry standard RTCM data message format and protocols (Annex A.1.3; [35.10]), ensuring interoperability between different brands of reference and user GNSS receivers. CORS installations typically comprise top-of-the-line receivers, with choke-rings antennas, capable of making multi-frequency, multi-GNSS measurements. The challenge is to install CORSs at sufficient density (minimum reference receiver separation) to permit single-base RTK with rapid AR (see schematic in Fig. 35.5). Note that this density of CORSs is the same as that for post-processed rapid-static and kinematic GNSS positioning using relative positioning principles.

RTK-GNSS implementations based on a network of reference stations (rather than a single reference station) are now common in many countries. Recall that one of the primary purposes of reference stations is to mitigate the impact on coordinate solutions of those systematic measurement biases and model errors that are spatially correlated [35.11, 12]. (The other is to provide the datum for differential positioning.) In the simplest configuration, it is assumed that in the case of two *nearby* GNSS receivers, when the measurements are made at the same time, and processed in an integrated observable model such as that produced by double-differencing measurements from a pair of receivers to a pair of GNSS satellites, there is no (or negligibly small) effect of atmospheric refraction biases and satellite orbit/clock errors on the baseline results (Sects. 21.3 and 26.1). Of course that assumption breaks down as the distance between the two GNSS receiver increases. Hence single-base RTK essentially requires

Fig. 35.5 CORS infrastructure for single-base RTK – indicating the *packing* of a network of continuously operating reference stations to support single-baseline, rapid-static, and kinematic positioning, so as to provide complete coverage over an area. Note the closer the user receiver is to a CORS the more reliable the GNSS position solution. Ideally the distance should be no greater than a few tens of kilometers (hence the graduation in color of the rings around each CORS indicating varying solution quality, from *green* for the highest to *red* for the lowest)

Table 35.7 Comparing single-baseline RTK and network-RTK GNSS positioning

	Single-baseline RTK	**Network-based RTK**
CORS infrastructure	● User owned CORSs; or Service Provider (SP) owns CORS ● Many CORSs for full area coverage	● Service Provider (SP) owns CORSs; or licenses raw data from organization operating network of CORSs ● Evenly distributed CORSs across service area
Service provision	● User-operated; or SP ● RTCM v2 or v3 messages	● SP; or CORS operator ● RTCM v3 N-RTK messages; or VRS-based customized RTCM v2 messages
Inter-receiver distances	● Tens of kilometers, preferably < 10 km for most reliable operations and/or ● rapid on-the-fly AR	● 50–100 km CORS spacing across service area ● < 30–50 km user receiver to nearest CORS
Configuration	● Nearest CORS ● Owner-operated; or subscription to SP ● Typically direct user-CORS connection	● User located within cluster of 3–4 CORSs ● Subscription to SP ● Central network or operations server/facility
Modeling of spatially correlated biases	● Cancellation of satellite-specific and atmospheric biases in double-differenced measurement model, by assuming biases identical to those of nearest CORS ● RTCM messages are *calibration* of biases at CORS location	● Cluster of CORSs surrounding user receiver location used to derive bias *correction surface* ● RTCM messages carry all information necessary for computation of location-specific biases to be applied as corrections to user receiver measurements
Communication options	● Terrestrial: ultra-high frequency (UHF), very high frequency (VHF), MF beacons, digital broadcasts, mobile Internet, etc.	● Terrestrial: mobile Internet ● Satellite communications
Accuracy	● Centimeter-level horizontal accuracy; 2× worse for vertical	● Similar accuracy to RTK; though with higher solution reliability
GNSS hardware	● Single-frequency GPS (but distances shorter and/or longer AR process); or multi-frequency receiver (preferred) ● Light-weight antenna, mounted on bipod or pole, or moving platform	● Multi-GNSS, multi-frequency receiver (preferred) ● Same antenna and mounting options as RTK
Applications	● Engineering surveying, machine guidance, and control (in agriculture, mining, construction, port operations, etc.)	● Same as RTK but operations less constrained by distance to nearest CORS; increased reliability due to multi-CORS configuration

the determination of baseline vectors radiating from the nearest RTK-capable reference station.

In contrast, a cluster of CORSs can be used to map the spatially correlated biases and errors across a CORS coverage area, and to apply these corrections to measurements at the user receiver location. This multi-CORS RTK-GNSS technique is often referred to as *network-RTK* (N-RTK), and its primary advantage from the point of view of the RT GNSS service providers is that the separation between user receivers and the surrounding CORSs can be of the order of 50–70 km or more [35.11–14]. The assumption that the systematic biases and model errors at the nearest CORS are the same as those at the user receiver location is replaced by the more realistic assumption that the biases and errors can be predicted at the user receiver location using a model of these biases and errors [35.15, 16].

N-RTK services can be supported by less dense CORS networks than single-base RTK services. Furthermore, the precise coordinates are not strictly determined relative to a single (or nearest) reference receiver, but has similarities to network-based (i. e., multi-station) static positioning. There are a number of implementations of N-RTK [35.14, 16, 24–26], of which the virtual reference station (VRS) scheme is the oldest and best known [35.15]. Some characteristics of RT-GNSS positioning are summarized in Table 35.7.

As a result of substantially more measurements and frequency-diversity, multi-constellation precise GNSS positioning will be able to be carried out with significantly greater distance-to-CORS than current N-RTK implementations – distances of over 100 km.

35.1.5 Precise Point Positioning

PPP (Chap. 25 and [35.19, 27–29]) is a GNSS carrier-phase-based positioning technique that can be used anywhere on the globe by a single user receiver – at

Table 35.8 Summary of precise GNSS positioning techniques – precise point positioning

- Typical scenario: one static or mobile user receiver; the latter on a variety of land, marine, aerial or space platforms
- User GNSS receiver may be single-frequency or multi-frequency; the latter being preferred as such hardware is identical to survey-grade GNSS receivers used for differential carrier-phase-based positioning
- Requires precise satellite orbit and satellite clock information from an external source; post-processed orbit and clock information available in the form of several open standard formats such as Standard Product 3 (SP3; Annex A.2.1; [35.17]); RT streams use open RTCM-SSR messages (Annex A.1.3; [35.10]) or proprietary messages
- No reference receiver requirements for user positioning (although a sparse global network of reference receivers are needed for the computation of satellite orbits and clocks)
- Datum defined by reference frame in which orbits, clocks, biases and other parameters are computed; typically the International Terrestrial Reference Frame (ITRF) (Chaps. 2 and 36; [35.18])
- Real-time or post-processed software does not require reference receiver measurements; observation modeling is more sophisticated (and complete) as it must account for all systematic biases and model effects (those that may have been mitigated or eliminated in between-receiver data differencing)
- Dual-frequency PPP is capable of providing accurate position solutions at subdecimeter level for kinematic positioning and at subcentimeter level for static positioning [35.19, 20]. For single-frequency PPP the positioning accuracy lies at the decimeter level with high-end receivers [35.21] and for kinematic positioning with low-end receivers at the submeter level [35.22]. The high accuracy of dual-frequency PPP is achieved after a relatively long convergence time in the range of 20–40 min, while the decimeter level accuracy of single-frequency PPP is achieved in minutes [35.23]. Additional infrastructure, in the form of networked reference receivers similar to that for N-RTK operations, is necessary for rapid convergence or reliable AR
- Communication links for RT-PPP include geostationary satellite communications, mobile Internet, and downlink messages on navigation satellite signals
- Applications include all those that cannot be easily addressed using relative GNSS positioning techniques, including operations in remote and offshore areas
- Factors impacting quality are similar to those for kinematic surveys, such as satellite-receiver geometry, number of satellites tracked and measurements that are made, but also quality of the model information, algorithm and whether AR is successful (or even required)

least without direct co-processing of CORS measurements, or application of differential correction or model information generated from such measurements (Table 35.8). PPP offers, therefore, considerable flexibility, making it well suited for remote locations (on land and offshore) where there is an absence of GNSS CORS infrastructure.

PPP relies on accurate satellite orbit and clock error information that can be obtained from sources such as the International GNSS Service (Chap. 33), or a number of commercial service providers, and the explicit modeling of a number of measurement biases and system effects that are assumed to have been eliminated when using GNSS in relative positioning mode. PPP can be implemented in post-processed mode or in real-time. The former uses accurate orbit and clock products that are available – depending upon the product that is used – immediately or up to several weeks after the survey task is executed. As an alternative to doing their own processing, surveyors can submit RINEX data files to one of several web processing engines [35.6–8]. The latter uses RT orbit and clock data streams broadcast via the Internet (in the case of the IGS Real-Time Service – IGS-RTS [35.30, 31]), or satellite communications links. These streams may be in proprietary message formats or in the RTCM State Space Representation (SSR) format (Annex A.1.3; [35.10]).

PPP can be done with single- and multi-frequency receivers. Fast single-frequency PPP requires next to orbits, clocks, and differential code biases, also ionospheric maps [35.23, 32–34]. The best possible position accuracy, a few centimeters or better, is obtained by using carrier-phase measurements from dual-frequency receivers. However, single-frequency receivers can provide decimeter accuracy at a reduced cost for the receiver and generally reach this level of accuracy much faster (few minutes) than a dual-frequency receiver does [35.23]. The convergence of dual-frequency PPP is longer (20–40 min) than that of single-frequency PPP as it initially depends on the relatively noisy ionosphere-free linear combination of the code data. Of course, after some time, the ionosphere-free linear combination of the carrier-phase data kicks in for dual-frequency PPP and becomes the determining factor for its high positioning accuracy.

The relatively long convergence time to reach the subdecimeter positioning accuracy, is one of the weaknesses of PPP. The positioning concept of PPP-RTK aims to address these weaknesses by reducing convergence times and improving positioning accuracy [35.35, 36]. It extends the PPP concept by providing single-receiver users, next to the orbits and clocks, also information about the satellite-phase biases. This information enables recovery of the integer user-ambiguities, thus enabling single-receiver AR thereby reducing the convergence times as compared to that of PPP. At present various different mechanizations of PPP-RTK are under development [35.37–39]. When combined with atmospheric corrections, PPP-RTK is rivalling the speed of standard N-RTK (Table 35.7). This is a fertile area of GNSS research and substantial improvements in performance are expected.

35.2 Geodetic and Land Surveying

With the progressive refinement of GPS geodetic surveying techniques to make them easier to use, and to increase their versatility, it was inevitable that the application of GPS technology would extend to include land (see below), engineering (Sect. 35.3), and hydrographic surveying (Sect. 35.4).

35.2.1 Geodetic Survey Applications

Geodetic surveying was the first civilian application of precise GPS positioning [35.3, 4]. It is concerned with the establishment, maintenance, and densification of *geodetic datums* – across a range of scales from the global, regional, national, and state territory down to an individual project application (though these are sometimes referred to as *control surveys*, Sect. 35.2.3). Geodetic datums are realized by ground marks with known ellipsoidal coordinates that can be used by any surveyor or engineer as starting coordinates for subsequent precise surveys, to support mapping, surveying, construction, or engineering activities. Precise GPS static positioning (Sect. 35.1.1) revolutionized geodetic surveying because it was able to replace the traditional, slow, labor-intensive terrestrial surveying techniques.

There are several innovations of modern GNSS geodetic surveying methodology that bear mentioning. The first one is the near universal installation of permanent GNSS reference receivers, or CORSs. CORSs range from single-receiver installations to vast networks of CORSs across entire countries (as in Japan's GEONET [35.40], Sweden's SWEPOS [35.41]), regions (e.g., EUREF's permanent CORS network [35.42]), and globally (e.g., the IGS network [35.43]).

Figure 35.6 illustrates some of the CORS sites across the continent of Australia. Note that this is a non-homogeneous CORS networks, with different agencies and individuals being responsible for their operation. This is typical of many national CORS networks. In effect such networks consists of numerous *subnetworks* of CORSs, some established by the federal government agency responsible for geodesy, some by state government departments, and others by private companies, local government authorities, universities, and even individual users. Furthermore the subnetworks may have different equipment configurations, different types of antenna mounts, and monumentation; supporting different user groups with a variety classes of service.

Figure 35.7 shows a typical choke-ring antenna (Chap. 17) with and without radome, installed on two typical designs of geodetic-grade monuments: concrete pillars and rigid tripods. The CORS coordinate reference point may not be the electrical center of the antenna but instead a physical reference mark on the top of the stable monument. Not shown is the instrument cabinet where the receiver itself is housed (together with communications, batteries, and other ancillary equipment), power systems such as solar panels, lightning protection, additional pillars or witness marks, etc. CORS installations such as these are a considerable in-

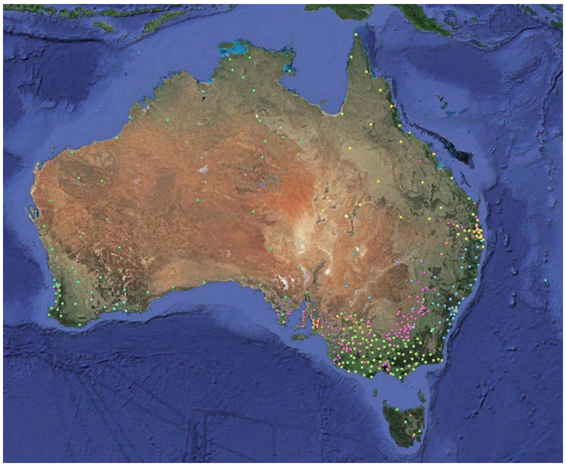

Fig. 35.6 GNSS CORS sites across Australia: an example of national CORS infrastructure that is non-homogeneous, with different owners and operators (*different colored dots*), to support a variety of GNSS positioning applications (and techniques), with an uneven distribution across the continent; note that private CORS sites operated by individual farmers, mining companies, universities, local council authorities, and others, are not shown (courtesy of Grant Hausler and ThinkSpatial)

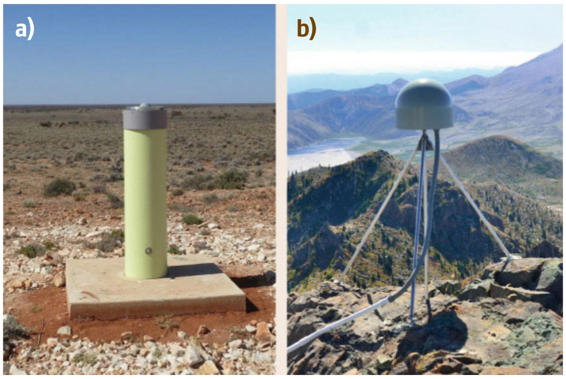

Fig. 35.7a,b Examples of geodetic-grade CORS installations: **(a)** on concrete pillar at Mulgathing, in South Australia, part of the AuScope national GNSS network (courtesy of Geoscience Australia); **(b)** drilled-braced monument at Coldwater Peak, part of the EarthScope Plate Boundary Observatory Mount St. Helens subnetwork (courtesy of Michael Gottlieb, UNAVCO)

vestment by an agency or organization in GNSS ground infrastructure.

The second innovation has been the availability of a variety of geodetic products and services, including those provided directly by the IGS (Chap. 33), by web services for GNSS measurement processing (Sect. 35.1.1), and by service providers for RT-GNSS positioning (Sect. 35.1.4), as well as the establishment of standardized data and transmission formats (Annex A) that support GNSS interoperability. This has also had an impact on GNSS measurement processing, allowing for the use of commercial software packages – as opposed to *scientific software* – for all but the most precise, long-baseline geodetic surveys.

The third concerns the nature of geodetic datums themselves. Increasingly national datums are aligned to, or defined by, the highest fidelity global geodetic datum: the International Terrestrial Reference Frame (ITRF; [35.18]). There are a number of reasons for this trend: (a) the global applicability of the ITRF, (b) the very precise set of coordinates and velocities of many GNSS CORSs (such as the IGS's network), (c) the ease of access via CORS tracking data and IGS geodetic products, (d) the well-defined datum epoch and documented maintenance procedures, and (e) its maintenance to the highest standards by the International Earth Rotation and Reference Systems Service (IERS; [35.44]).

Several GNSS geodetic surveying *methodologies* that can be used to distinguish these types of applications from routine engineering and mapping applications that rely on static and kinematic GNSS positioning techniques are summarized in Table 35.9. Note that geodetic surveying assumes the use of *geodetic-grade* multi-frequency, multi-GNSS receivers, with choke-ring or multipath-mitigating antennas, set-up on stable monumentation (Fig. 35.7).

The geodetic survey applications may, at first glance, appear simply as examples of static surveys; however modern geodesy recognizes that no object on the surface of the Earth has zero velocity with respect to the ITRF. The mission of modern geodesy is to determine and monitor the coordinates of sample points in order to improve our knowledge of geophysical processes that have ground motion/deformation signatures [35.45, 46].

Ground deformation surveys are undertaken to measure the change in the coordinates of stable points or monuments fixed to the Earth's surface. The points may move in a horizontal or vertical sense, or in three dimensions, with signature characteristics across a wide range of time and spatial scales, from continental motion of the order of millimeters or centimeters per year, to rapid ground shaking during an earthquake reaching magnitudes of many decimeters. There are a number of subcategories of deformation surveys, such as building/structural monitoring, ground subsidence (due to underground fluid extraction or mining) or inflation (due to build-up of magma below volcanoes), tide gauge stability monitoring, and local tectonic fault motion.

Given the sophistication of scientific GNSS analysis (Chaps. 34, 36, and 37), the computation of positions to subcentimeter accuracy may involve the determination of not only the geodetic coordinates of the GNSS receivers, but also improved estimates of receiver and satellite clock errors, signal biases, GNSS satellite orbits, atmospheric delay biases, and Earth rotation/orientation parameters. The continuous processing of measurements from hundreds of globally distributed CORSs, by a large number of organizations, coordinated by international geodesy initiatives, is a geodetic enterprise that defies easy partitioning into different geodetic surveying applications.

35.2.2 Land Surveying Operations

The goals of GNSS land, engineering, and hydrographic surveying operations are to coordinate many points on the ground, in the air, or on the sea as quickly as possible to the accuracy required by the client and with the coordinate information expressed in relation to a project, map, or geodetic datum.

It is possible to distinguish between three categories of *point coordination*. One is the task of determining coordinates of points or features that exist. Examples include control surveys, detail or topographic surveys, surveys of buildings and land boundaries, built struc-

Table 35.9 Comments on GNSS geodetic surveying methodologies

Field campaign surveys (baseline mode)	● Application: Densification of geodetic control across a local area ● Minimum of a pair of stationary GNSS receivers, operated in single-baseline mode, baseline lengths typically several tens of kilometers ● Conventional static positioning (Sect. 35.1.1), with observation sessions ranging from an hour to many hours ● Considerable redundancy through multiple occupations of monumented ground control points ● Single-baseline measurement processing using commercial software in post-processing mode ● Network solution through secondary adjustment of baselines, with known control point constraints applied to ensure consistency and connection to surrounding geodetic control, see Fig. 35.1.
Field campaign surveys (multistation mode)	● Applications: – Establishment of a primary geodetic datum network across a large (national or continental) area – Densification of datum across hundreds of kilometers – Rapid datum maintenance geodetic surveys after major earthquake – Multi-campaign GNSS surveys to detect small land or ice movement over periods of years ● Multiple receivers deployed across a network of monumented ground control points, in a multi-session mode, to ensure that all control points are occupied by GNSS receiver at least once (and ideally twice, or more) ● Static observation session lengths typically from several hours to 24 h (or even longer) ● Data post-processing options: – Simultaneous processing of all observed data files in scientific software, with datum constraints applied directly (i. e., ITRF coordinates of some control points) and perhaps also indirectly (use of precise IGS satellite orbit products) – the most rigorous approach – Use web-based processing services such as AUSPOS [35.8], OPUS [35.6], CRCS-PPP [35.7], etc., that link field surveys with surrounding IGS and/or national CORS – however not as rigorous as simultaneous processing of all campaign data in scenario above
Continuously Operating Reference Stations (CORS)	● Applications: – *Active* geodetic control points realizing national datum; and possibly also supporting commercial RTK/N-RTK services – Part of (national or international) network of observing stations, whose data is used to generate geodetic products such as coordinate time series, satellite orbits or clocks, ionospheric and tropospheric parameters, etc. – Instrumentation primarily intended for monitoring tectonic motion, localized ground or structural deformation, etc. ● Observation data typically streamed to central data or analysis center, where data processing may be carried out in real-time, near-RT, or post-processed mode depending upon application ● CORS density may vary from several tens to several hundred (or even thousand) kilometers ● Data analysis may be via: – Scientific software similar to that used for post-processing of field campaign data – Specialized software for RT processing to geodetic modeling standard – Commercial baseline or multi-station software to support RTK/N-RTK operations

tures, etc. The second is determining the position of a moving object or platform, that is, its trajectory, as in the case of a land vehicle, an aircraft, or a ship. The third is to determine the location of a point that has a prespecified 3-D coordinate – as in set-out surveys on engineering construction sites, or way-points that must be navigated to. The latter two types of positioning are discussed in Sect. 35.3.

GNSS technology intended for use by surveyors and engineers needs to be largely automatic, reliable, and easy-to-operate. For high-productivity operations a commercial off-the-shelf package is preferred – receiver hardware, processing and control software, and ancillary instrumentation. The receiver signal tracking and processing electronics are essentially identical to geodetic-grade GNSS receivers, and hence are capable of the same measurement quality – although the choke-ring antenna is usually replaced by a light-weight survey antenna (Chap. 17). Furthermore there has been considerable product refinement in survey-grade GNSS receivers, which nowadays are compact, rugged, and come in a variety of form-factors. The most common instrument form-factor is a single unit (without cumbersome antenna or power cabling) containing receiver electronics, antenna, battery, wireless communications, and data memory, able to be placed on a survey pole or other survey instrument (Fig. 35.8), or on a moving platform (Fig. 35.3).

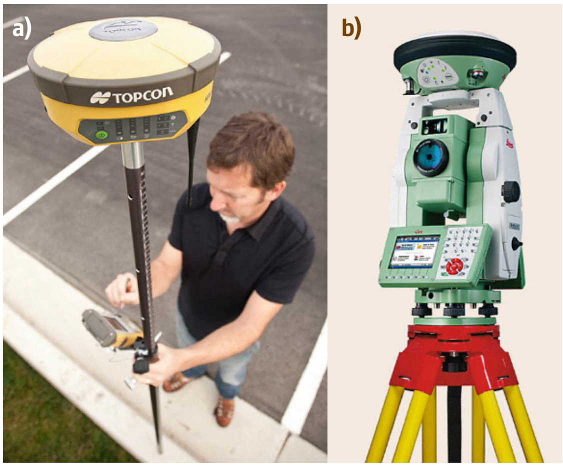

Fig. 35.8a,b Some examples of GNSS receiver form-factors for land surveying applications: **(a)** pole-mounted GNSS receiver as used by surveyors and engineers to determine coordinates of static points-of-interest (courtesy of Position Partners); **(b)** GNSS receiver mounted on top of a Total Station supporting integrated survey operation (courtesy of Leica Geosystems) ▶

The typical field deployment requires the surveyor's GNSS receiver to move from one point whose coordinates are to be determined to another, and to continue this procedure until all points have been *visited*. The reference receiver remains set up on the point of known coordinate, and hence the 3-D baseline vectors radiate from that reference station to the points being surveyed, as in Fig. 35.2. This configuration is familiar to land surveyors, as *radiation* is the most common means of determining the coordinates of points – for example, by means of azimuth, distance and vertical angle measurement made from a Total Station instrument (Fig. 35.8) set up on a portable tripod over a fixed ground mark. In

Table 35.10 GNSS land surveying applications and operational issues

Control and deformation surveys	In a continuum of static positioning applications ranging from those that can be identified as geodetic surveying (Table 35.9), to local or project control with the following distinguishing characteristics: ● Generally employ static or rapid-static techniques (Table 35.4), using commercial data-processing software, although RTK/N-RTK mode sometimes used (though with more redundancy and greater care than typical kinematic surveys) ● Non-permanent ground marks (e.g., drillholes, nails in kerbs), Datum typically construction project-based, although linked to the national datum at epoch of observation if using RTK/N-RTK ● Purpose is closely tied to nearby engineering or surveying activity ● Project extent is typically a few to tens of kilometers across ● Deformation surveys are associated with construction activities, or focused on built structures, and require either continuous surveys (or re-surveys at regular intervals) of critical points
Topographical surveys and mapping	The rapid determination of the coordinates of many natural surface points or constructed features, across a comparatively small area, with the following characteristics: ● *Direct* point coordination by GNSS, using rapid-static, stop-&-go, or kinematic surveying techniques (Sect. 35.1) ● *Indirect* mapping, where GNSS is used to determine the precise coordinates of a mapping sensor such as a digital camera or laser scanner ● Areal extent is a few hundred square meters to tens (and perhaps hundreds) of square kilometers ● Results not required in real-time, though RTK/N-RTK surveys may have lower operational costs ● Results may be presented in variety of forms suitable for import into computer aided design (CAD) or geographic information system (GIS) software
Cadastral surveys	Cadastral surveys address legal questions such as: where are the boundaries of land parcel, what rights and responsibilities are attached to a land parcel, and the creation of new land titles following subdivision or redevelopment, and hence have the following characteristics: ● Due to the considerable variety of national and state land titling and cadastral boundary systems, guidelines on what surveyors must measure, to what accuracy, and what information must be registered, will also vary with national or state jurisdiction ● There is considerable scope for use of GNSS surveying techniques for cadastral surveys of rural properties; use in urban areas is more problematic ● There are very few coordinate-based cadastres, hence GNSS-derived coordinates must be transformed into distances and bearings to be useful for cadastral mapping applications ● Survey project extent is typically a few hundreds of meters to perhaps a few kilometers across

the GNSS configuration, the surveyor may not even be responsible for the operation of the reference receiver, and is merely using the RT corrections or the recorded data files (in the case of post-survey computations). Although the algorithms underlying Network-RTK take advantage of data from a network of CORSs, as far as the user is concerned the *packaging* of N-RTK messages is such that it mimics the RT processing of a baseline radiating from a nearby CORS to the user receiver (Table 35.7).

GNSS land and engineering surveying procedures are typically prescribed in national or state standards and recommendations, or contract guidelines, especially for cadastral surveys or datum control surveys (Table 35.10). These standards or guidelines may *suggest*, *recommend*, or *define* the hardware requirements, field observation procedures, ground mark design, quality assurance processes, and minimum and maximum thresholds for geometric constraints such as baseline lengths, network quality checks, number of tracked satellites, and so forth. Nowadays, because GNSS is an all-weather system available 24 h a day that does not require intervisibility between survey receiver and reference receiver(s), there is no longer the need to plan for the best time of day to conduct surveys so as to ensure adequate satellite geometry, or to carry out detailed reconnaissance of the survey area. It is beyond the scope of this chapter to delve into national standards or recommendations for GNSS land, engineering, and hydrographic surveying applications; however the reader is referred to documents such as [35.47–53].

35.2.3 Land Surveying and Mapping Applications

The range of land surveying and mapping applications is very broad (Table 35.10). However, GNSS is but one technology in the land surveyor's toolkit, best suited to clear sky view conditions that ensure that measurements can be made to as many GNSS satellites (with favorable geometry) as possible, and where the raison d'etre is the determination of position (i. e., coordinates). While the former is a constraint on the operating environment, the latter acknowledges there is a broader set of survey services than just point coordination, which include azimuth or alignment determination, horizontal or vertical offset measurement, and precise physical height (difference) measurement.

The complexity of land and engineering survey tasks requires professional judgement: (a) to select the appropriate technology and operational techniques, (b) to conduct or oversee the careful execution of the field survey, (c) to process measurements taking into account all errors and constraints, and (d) to generate the outputs required by the client. The reader is referred to land survey texts for details concerning surveying principles, technologies, and applications [35.54, 55].

Control surveys are similar to geodetic surveys (Sect. 35.2.1); however they are carried out at local or construction project scales [35.54, 55]. The objective is to determine the coordinates of ground control points referred to a project, mapping, or geodetic datum during a field survey campaign. These control points may be of a temporary nature, intended only to be used over a project lifetime, or established as permanent marks (Fig. 35.9). The control points would typically be used for subsequent project surveys for guiding construction, mapping terrain and structures, lower order surveys, or for monitoring ground or structural deformation.

Deformation surveys are a form of geodetic surveying in which the displacement of a GNSS receiver, relative to some *rest* position or position at some measurement epoch, is monitored over time (Sect. 35.2.1). The receiver may be mounted on a deforming engineered structure [35.56], or it may be set up on ground marks in areas of ground surface movement. The distinctions between geodetic deformation surveys and land deformation surveys are largely of a semantic nature; however there are a number of deformation survey scenarios that could be used to distinguish between geodetic, land, and engineering deformation survey applications. It is common to partition those deformation surveys that are sensitive to geophysical or natural processes, such as tectonic motion, volcanic activity, land uplift, or subsidence, from those that measure displacement of engineered structures or monitor deformation with anthropogenic sources such as underground fluid

Fig. 35.9a,b Establishing coordinates of control marks using GNSS: **(a)** setting up a GNSS receiver/antenna set up over rural control mark using a bipod; **(b)** GNSS receiver/antenna mounted on tripod to collect measurements for establishing geodetic control at a mine site (courtesy of Position Partners)

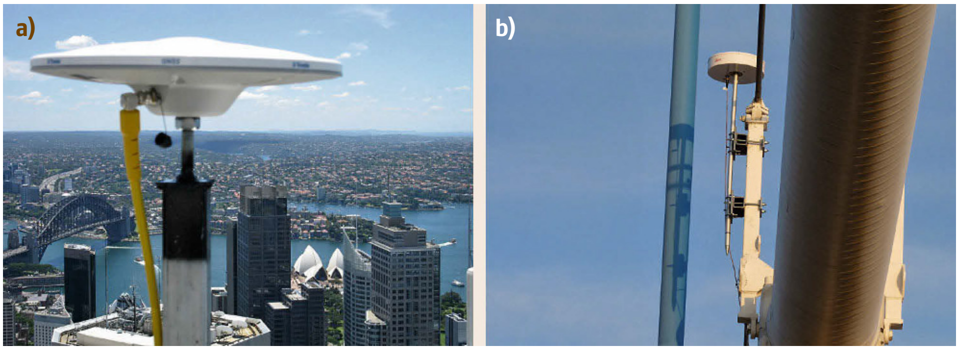

Fig. 35.10a,b GNSS installed on structures for displacement measurements: **(a)** on a tall building in Sydney, Australia (courtesy of Ultimate Positioning); **(b)** attached to support cables of the Severn Suspension Bridge, connecting Bristol to South Wales, UK (courtesy of Gethin Wyn Roberts & Chris J. Brown)

extraction and mining. The former may require more permanent monitoring systems, whereas the latter imply periodic measurement campaigns or monitoring that takes place only over a limited period of time.

Figure 35.10 shows two examples of GNSS installations for deformation monitoring – one on a tall building and the other on a cable suspension bridge. The mode of GNSS positioning may be continuous or episodic, and typically requires some form of time series analysis of computed coordinates in order to detect trends in changes in the coordinates or to determine spectral signatures of vibrating receivers. In addition, GNSS may only be one of a number of technologies that are used in such applications. Other instrumentation include inclinometers and accelerometers.

Topographical surveys are sometimes referred to as *detail surveys*, and are examples of small-area mapping [35.54, 55]. They are similar to surveys carried out using terrestrial survey technology such as Total Stations, except that line-of-sight visibility between reference point and survey point is not necessary. During such surveys the coordinates of ground features (natural and engineered) are determined, including the assumed locations of buried utilities, as well as sufficient sampled surface points to allow the terrain undulations to be modeled as gridded height values, triangulated irregular network points, or contour lines. The output of such surveys is a set of coordinates and feature attributes that permit the data to be exported to CAD or GIS software packages.

Mapping surveys are concerned with the determination of the coordinates of many points across an area for the purpose of describing the terrain, structure, or built environment in a *spatial* sense [35.54, 57]. Typically what results is a database of coordinates (the *where* information), attributes (the *what* information), and topology (the *how connected* information) of a sufficient number or density of natural or constructed features to ensure a representation of reality at the largest scale of interest. GNSS may be used to directly coordinate the feature to be mapped, or to determine the coordinates of the mapping, imaging, or laser scanning sensor over time, from which coordinates of *pixels* or *point-clouds* are derived in a secondary process.

Cadastral surveys are a special form of survey for the determination or marking-out of land property boundaries [35.58]. In some countries boundaries are defined by coordinates, and hence the survey task is to calculate where the *real* boundaries are with respect to physical structures such as fences, roads, or buildings. However in many countries land boundaries are defined by distance and azimuth of boundary lines as described in registered certificates of titles (in countries that use the Torrens System of title) or in deed documents (for countries that do not) [35.58]. They may also be depicted graphically in cadastral maps. In such cases the GNSS coordinates are used to derive distance and azimuth quantities, and are considered to be one form of evidence that can be used to reconstruct the original land parcel boundaries. GNSS land surveying techniques are particularly useful for rural cadastral surveys, or where new land property boundaries are established as a result of land redevelopment or infrastructure construction projects. [35.48] is an example of GNSS guidelines for cadastral surveying.

35.3 Engineering Surveying

Much of what is stated in Sect. 35.2 with regard to how GNSS is used for land surveying and mapping is also relevant to engineering surveying (see below) and hydrographic surveying (Sect. 35.4). The accuracy requirements are essentially the same, as is the receiver hardware. In addition, there is a reliance on service providers for a variety of augmentation services, and in some cases auxiliary data, to support centimeter-level positioning accuracy. There is an unrelenting drive by GNSS user equipment manufacturers to challenge current operational constraints in order to promote even greater uptake of GNSS technology for engineering applications. Hence some of the most significant innovations are occurring in the GNSS technology that addresses these applications.

Surveys for the construction of roads, bridges, buildings, tunnels, mines, and other structures are based on the same geometric principles and use similar field procedures as land surveying applications [35.53, 54]), and require: (a) the determination of the coordinates of existing ground marks or features, or (b) the identification of marks or points at predefined coordinates to guide construction or machinery. Surveyors are engaged on such projects at all phases of construction, including the original determination of land, building, or marine boundaries. This section focuses on terrestrial engineering applications. Section 35.4 discusses offshore engineering and charting applications.

35.3.1 Engineering Surveying Real-Time Operations

One defining characteristic of almost all GNSS engineering surveying applications is their demand for accurate positioning in real-time. In fact without such capability the application may at best not be cost-effective, or at worse not be feasible at all. RT precise positioning applications include: (a) precise navigation between predefined way-points, such as for vehicle guidance and control applications; (b) construction set-out of formwork, surfaces, and structures; (c) open-cut mining operations; (d) precision agriculture, especially so-called *control track farming*; and (e) rapid mobile mapping. In some cases GNSS is combined with other positioning/guidance technologies – such as laser or vision-based systems, or inertial measurement sensors – to ensure continuous positioning during short GNSS outages, or to provide additional platform orientation information.

RT-GNSS implies no delay between measurements made by the GNSS receiver and the coordinate information being generated from measurement processing. Of course there cannot be zero delay; however, it will be assumed that either a delay of one or more seconds is not critical, or computational techniques can be applied to predict position at predefined intervals. RT-GNSS positioning generally implies an *always-on* capability hence the operation of the reference receiver(s) and associated services, such as communications, computing facilities, power, etc., must be continuous, because in addition to high accuracy there is also an increased demand for high *integrity* – machine or vehicle guidance require reliable coordinate solutions.

The flexibility of RT-GNSS positioning is greatest when industry standards for data message transmission, such as those defined by RTCM (Annex A.1.3), are adopted, enabling GNSS receivers from different manufacturers to operate together using the same over-the-air transmissions. The value of industry standards is most obvious in RTK or N-RTK operations (Sect. 35.1.4).

The central role played by RT-GNSS service providers must be acknowledged. Some of the reasons why many users these days take advantage of RT-GNSS services are: (a) the need for continuous and reliable RT operations; (b) the widespread adoption of RTCM data transmission formats; and (c) the high cost/complexity of operating reference receivers. RT-GNSS service providers include private companies, academia, research institutions, and government agencies.

CORSs installed by RT-GNSS service providers typically consist of geodetic-grade receivers, with choke-ring antennas, capable of making multi-frequency, multi-GNSS measurements. RT-GNSS places considerable demands on communication links; between individual CORS receivers and (typically) a central server to manage the transmission of CORS measurements, and for transmission of correction messages to RT-GNSS users. Furthermore, the reference receivers should have the tracking capability to at least match that of the most sophisticated user receiver in order that, for example, RTCM data messages for all visible GNSS satellites and signals that could be used can be broadcast to users. Besides, CORS positioning infrastructure may be used to support GNSS geodesy applications (Sect. 35.2.1) – however the monument on which the GNSS antenna is fixed must be stable.

In contrast to multi-purpose or commercial CORS networks referred to above, there are many RTK systems installed by individual user/operators, especially in the precision agriculture and open-cut mining user segments. These users own several survey-grade GNSS receivers, operate one as a base station, install the other(s) on one (or more) agricultural or mine vehi-

Table 35.11 GNSS engineering surveying applications and operational issues

Construction surveys	Construction surveys support engineering and infrastructure projects, and have the following characteristics: ● GNSS is one technology used by engineers and surveyors on building/construction sites; other technologies must also be used and hence a seamless transfer of coordinates between different construction survey instrumentation is necessary ● The immediacy of the tasks on building/construction sites demands the use of real-time GNSS positioning techniques such as RTK/N-RTK; and with increased automation of construction processes there is the need to ensure integration of all types of GNSS positioning on construction sites ● Variety of positioning challenges, ranging from coordinating fixed points (similar to topographical surveys), determining coordinates of moving GNSS receiver trajectory, to navigating GNSS receiver to a predefined spatial coordinate ● Construction project datum is used, typically requiring the transformation of RTK/N-RTK generated coordinates into the project datum ● Survey extent is typically a few hundreds of meters to perhaps a few kilometers across
Construction and mining machinery automation	There is a trend to increased automation of construction and mining machinery automation, from human-in-the-loop implementations to full autonomous operation, implying: ● High-accuracy and high-integrity real-time GNSS positioning availability ● Centimeter-level accuracy, though with backup technology options when GNSS is unavailable ● Positioning typically is intended to navigate the vehicle to coordinated points, hence requiring adjustment of the vehicle's state from *current* coordinates to *target* coordinates ● Tight integration with guidance or control systems, and hence often factory-installed by the machine manufacturers themselves ● Coverage areas typically up to a few kilometers across
Agriculture	Similar to construction machinery automation applications, with the following unique characteristics: ● Coverage areas may be many kilometers across ● The conditions for RT-GNSS are typically more favorable with respect to sky visibility conditions ● The accuracy requirements may be more relaxed, ranging from meter-level for standard precision agriculture, to subdecimeter-level accuracy in the case of *control track farming* ● Horizontal positioning
Mapping	Mobile mapping applications are characterized by: ● Variety of platforms – terrestrial, airborne, marine ● Variety of mapping sensor technologies, ground sampling (or resolution), field-of-view, cost, operational constraints (e.g., height, range, speed, etc.) ● Accuracy requirements may be relaxed considerably, depending upon the mapping methodology that is used ● Real-time positioning is in general not essential ● Survey extent may vary from a few kilometers to many tens of kilometers across

cle, and implement a *closed* RTK service via a UHF radio link between the receivers. Such a configuration is not optimal, for no other reason than the wasteful duplication of base stations across a coverage area. It is expected that, over time, such GNSS users will decommission their own base stations and instead subscribe to RT-GNSS services.

35.3.2 Engineering Surveying Applications

These type of surveys may be considered a subcategory of GNSS *land surveying applications* (Sect. 35.2.3), and are those that are: (a) undertaken on land, (b) associated with construction or mining activities, (c) limited to a project area, (d) constrained to a project time scale, (e) involve machinery, and (f) extensively use RT-GNSS techniques. Examples of engineering surveying applications are listed in Table 35.11, and discussed below.

Construction surveys address the different positioning requirements of civil engineers and building professionals during the construction phase for any engineered structure [35.54]. High-accuracy GNSS technology is used in place of traditional terrestrial surveying instrumentation for setting out of trenches or formwork for concrete pours, checking verticality (or horizontality) of construction, or measuring the dimensions of structural component, such as walls, beams, pipes, cables, and so on (Fig. 35.11). The utility of being able to do this in real-time is crucial in order that immediate action can be taken, whether in the form of routine execution of

Fig. 35.11 GNSS as typically used by surveyors on construction sites: here is shown a pole-mounted GNSS receiver which is being used to either coordinate a point-of-interest or to mark a point whose coordinate is provided in order to set out formwork for concrete pouring, laying of cables, pipes, or services, etc.; typically operating in real-time mode (courtesy of Leica Geosystems)

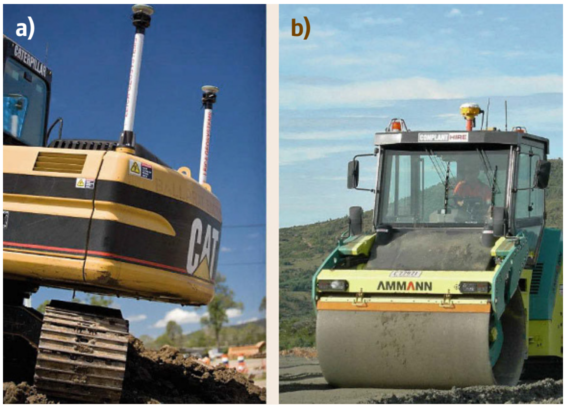

Fig. 35.12a,b GNSS receivers installed on construction machinery to guide excavations **(a)** and grading **(b)**. Note in **(a)** that two antennas/receivers are installed to allow for GNSS to determine not just position, but also orientation in 3-D so that the bulldozer blade may be manipulated to excavate an inclined design surface (**(a)** courtesy of Leica Geosystems, **(b)** courtesy of Ultimate Positioning)

engineering tasks or to allow for on-site modification or adjustment of construction plans. These surveys are, in many respects, the most demanding applications of high-accuracy GNSS technology because of the variable conditions on construction sites. For example, there may be significant shading of the sky, considerable vehicular and human traffic, dangerous/noisy/dirty conditions, variable wireless coverage, and a number of different coordinate datums, to name but a few. The engineering surveyor must be capable of executing their tasks in an often stressful and unpredictable environment. Furthermore, GNSS is but one tool at their disposal. However, there is a trend to increased *automation* of excavating, drilling, concreting, paving, laying of preformed slabs, erection of walls or formwork, removal of waste material, etc., which implies instantaneous guidance and/or control of heavy machinery using high-accuracy, high-integrity GNSS technology, possibly supplemented with laser, vision, and inertial systems to improve availability and reliability.

Construction machinery automation of graders, bulldozers, tractors, trucks, and specialized vehicles or machinery brings with it improvements in productivity [35.59]. This productivity can be measured in many ways, including faster and more accurate construction, longer work days, with fewer errors, smaller construction workforce, less injuries to workers, and reduced fuel use. Early examples of machine automation for construction environments are closely related to the technology supporting precision agriculture, especially *control traffic farming* [35.60, 61] where RT-GNSS is used to guide farm machinery with an accuracy that ensures the vehicle's wheel ruts are always in the same *track*. This requires subdecimeter, repeatable positioning accuracy, in real-time on a continuous basis. Construction equipment can be similarly *guided* along *tracks*, ensuring road centerlines are set out according to design coordinates, or the concreting of airport runways and taxiways is carried out very precisely in a vertical sense. This is in contrast to kinematic GNSS positioning as illustrated in Fig. 35.3, where the GNSS instrument is used to map the terrain as it actually is. Figure 35.12 shows GNSS receivers mounted on construction machinery.

Over the next decade the degree of autonomy of construction vehicles and machinery will increase significantly, and construction, mining, and agriculture will likely be the largest markets for high-accuracy GNSS positioning systems. Machine automation can be implemented in a variety of scenarios, from simply aiding the operator via in-cabin computer displays that show actual vehicle tracks and design lines or surfaces (Fig. 35.13) through radio-controlled machinery by operators who may not even be located on the site to fully autonomous robots that operate with no human intervention at all. These applications require centimeter-level positioning accuracy provided by RT-GNSS. However, the level of integrity may range from relatively low – with the operator merely informed when positioning is unavailable, who then controls the machinery manually – to very high integrity in the case of full machine automation. Yet even in this mode the addition of vision or scanning sensors can provide enough *situation-awareness* for an autonomous vehicle to respond to loss of GNSS positioning capability.

Fig. 35.13 Inside cabin of GNSS-assisted machinery – one or more GNSS receivers/antennas (multiple antennas provide vehicle orientation information) are installed on construction machinery and real-time solutions for position (and perhaps orientation angles) of the reference point on the vehicle are displayed to the machinery operator on a controller device together with the planned trajectory of the machinery so that the excavation may be carried out according to design (courtesy of Ultimate Positioning)

Mining survey applications are subcategories of several GNSS land and engineering surveying applications [35.54, 55]. It must first be acknowledged that GNSS can only be used for open-cut mine operations, which are similar to construction project sites. On such sites the full range of surveying and positioning tasks are required: mapping, set-out, construction, volume surveys, machine guidance/control, and vehicle fleet management/tracking. As with construction site GNSS surveys, the area of operations is rather constrained – perhaps just a few kilometers across – and the dirty, dangerous, and typically extreme environmental conditions place heavy demands on technology. The challenge for RT-GNSS users in deep open-cut mines is that with increasing depth, the proportion of open sky that a GNSS receiver *sees* decreases rapidly. This is especially the case when surveyors or GNSS-guided machinery are working near steeply sloping mine walls. It was the need to increase the number of visible satellites under such conditions, beyond the available GPS constellation, which has driven the adoption of multi-GNSS receivers for such critical applications – initially GPS+GLONASS, but nowadays capable of tracking signals, and processing measurements, from other GNSS constellations.

35.3.3 Project Execution and Related Issues

The applications listed above imply operations over relatively small areas. GNSS must compete with terrestrial surveying technologies, and hence must be a cost-effective and easy-to-use technology. It should be used only in project environments that are optimal for rapid and reliable AR, and for which there is very good sky visibility. Unlike GNSS geodetic or land surveying projects, reconnaissance *prior* to the use of GNSS for engineering surveys is not carried out.

In addition, given the construction project scale of most engineering surveying applications, the issue of the coordinate datum is different to that for geodetic surveying, and perhaps even to land surveying. The datum is typically of local relevance, with coordinates often expressed in a horizontal map projection for ease of graphical display and spatial analysis. The vertical component is measured in terms of physical heights, not ellipsoidal heights (or height differences). Hence *horizontal surveys* are typically carried out, with *vertical surveys* often conducted using one of a number of lev-

Fig. 35.14 Mobile mapping system (MMS) installed on a road vehicle. The system comprises multiple imaging sensors (cameras pointing forward, sideways, and backward), a laser scanner (on the top of the vehicle), a GNSS antenna (at the top of the van), and an inertial navigation system for platform orientation (box on rack next to laser scanner). Note also that this particular MMS is carrying additional sensors (mounted low to the ground) for radar imaging of the road surface and detection of cracks in pavement (courtesy of Charles Toth)

eling techniques, including the GNSS ellipsoidal height + geoid height-leveling method [35.62].

However, RTK/N-RTK operations imply that coordinates are determined in the datum defined by the coordinates of the CORSs – which typically are expressed in a national reference frame. In some instances, for example, at a mine, dam, and other large construction site the reference receivers are operated by the project surveyors, and the RTK/N-RTK settings may be adjusted to output GNSS coordinates in the local project datum or coordinate system. The situation regarding RT-PPP is more complex as the point positioning technique derives its datum from the precise GNSS satellite orbits, and these are invariably in a globally relevant, stable reference frame such as the ITRF [35.18]. In summary, for RT applications GNSS-derived coordinates may need to be transformed into the local project datum by the GNSS field instrumentation before they can be used by engineering surveyors, or by the machines that are guided by RT-GNSS systems.

With respect to GNSS-enabled *mapping* (Sect. 35.2.3), although the mapped points may be stationary, these days geospatial data acquisition is carried out from a moving platform (e.g., equipped with a camera or laser scanner) such as a vehicle (Fig. 35.14), aircraft (or unmanned aerial vehicle), or ship. Maximum flexibility is afforded by *post-survey* processing of recorded GNSS measurements. In addition, decimeter-level or lower accuracy is typically adequate allowing for relaxed instrument or field operational requirements. Furthermore the 3-D orientation or attitude of the mapping sensor is typically determined using inertial technology (Chap. 28). The operational guidelines, quality control procedures, and accuracy requirements for different mobile mapping platforms will vary considerably. It is beyond the scope of this chapter to discuss in detail the range of mobile mapping applications, the imaging and scanner technologies that are available, the mapping analysis methodologies that can be used, and the operational guidelines to be followed. Readers are referred to [35.63], and similar articles in geospatial magazines and international conference proceedings, for the latest developments in this rapidly evolving technological field.

35.4 Hydrographic Surveying

Much of what is stated in Sect. 35.3 with regard to how GNSS is used for engineering surveying and mapping is also relevant to hydrographic surveying in support of offshore engineering and sea floor charting. Offshore engineering associated with pipelines, undersea cables, breakwaters, harbor works, and freestanding structures has similar requirements for preconstruction surveys; for subsequent support or control of operations during the construction phase; and, finally, postconstruction *as-built* surveys. Furthermore, charting surveys require positioning of the moving platform, similar to terrestrial or aerial mapping, although the undersea imaging technologies are very different.

35.4.1 Hydrographic Surveying Applications

Although land, engineering, and offshore surveying share many geometric principles [35.53], the offshore operational environment is in many respects more challenging [35.64]. The environment is more corrosive, the marine platform (such as a ship, drill-rig, dredging vessel, small boat, or autonomous underwater vehicle) is in continuous motion, and the distances from marine receivers to shore-based reference stations may be longer than is the case for most land-based applications. On the other hand sky visibility is typically very good.

Prior to the introduction of GNSS, the techniques for offshore positioning were less accurate, more complex, and more expensive than those used on land. Invariably as the distance from shore increased, the positioning accuracy reduced, and the *electronic* positioning technology that could be used changed. The positioning technology was classified as *short-range*, *medium-range*, or *long-range*, referring to the distance over which transmitted terrestrial ranging signals could be detected [35.65, 66]. The introduction of the Transit Navy Navigation Satellite System (also often referred to as *Transit Doppler*) to the civilian community in 1964 [35.67, 68] made it possible to undertake hydrographic survey operations anywhere in the world, without relying on shore-based signal transmitters. The Transit Doppler system was retired in 1996, but GPS further revolutionized hydrographic surveying and maritime navigation. Nowadays, GNSS is used for all (surface) marine positioning requirements [35.66].

Hydrographic surveying operations can be partitioned into two general classes [35.64, 65]: (a) charting and (b) offshore engineering activities (Table 35.12). As with land-based mapping and surveying applications, some require RT positioning while others may be addressed using post-processed techniques.

Charting is an operation in which a mapping sensor aboard a ship, or towed *fish*, moves in a pattern that ensures an entire area of the seabed is imaged, or *illu-*

Table 35.12 GNSS hydrographic surveying and marine applications

Harbor and river operations	● Typical applications: small-scale surveys of river or harbor bed, positioning of buoys, cables or pipelines, vessel-docking maneuvers, etc. ● Scenarios vary: positioning vessel or structure; measuring vessel's trajectory; navigating to predefined locations ● If accuracy demands it, RTK/N-RTK techniques are used
Dredging	● Similar to land-based engineering surveys, requiring precise real-time spatial positioning of vessel-mounted excavating equipment ● Attitude of vessel may be determined using a GNSS multi-antenna system, although using an inertial system is a common option ● Typically conducted close to shore, permitting the use of standard RTK techniques
Offshore engineering	● Typical applications: construction of breakwaters, piers, shore defences, wind or tidal energy platforms, gas and oil-drilling platforms, pipelines, cable laying ● Operations will vary from being very close to land, to mid-ocean ● Accuracy requirements will vary considerably, hence there is a wide choice of GNSS positioning techniques ● Real-time positioning is typically required
Charting	● Can take place well offshore, for which differential kinematic positioning techniques may be impracticable ● Horizontal positioning accuracy is defined by international standards, and rarely requires the use of carrier-phase-based techniques ● Chart Datum is typically lowest astronomical tide, hence vertical (ellipsoidal) positioning of sonar sensor not required, although the vessel's heave motion is measured so as to correct raw depth measurements ● Real-time positioning is rarely a requirement for charting

minated, by transmitted sound waves, and the reflected signals recorded – the acoustic sensor may be a side-scan sonar or an echo sounder [35.64, 69]. Much like an airborne or vehicle-mounted camera or laser scanner, the return signals are processed to generate a 3-D map of the (reflecting) surface (Fig. 35.15). As with other types of mapping, both the *position* and *orientation* of the sensor must be measured so that direct georeferencing techniques can be used. In the case of active mapping systems such as sonar or laser scanners, the position and orientation of both the signal transmitter and the signal receiver are required, while this requirement needs to be fulfilled only for the imaging sensor. Unlike land GNSS applications, for which there are no internationally recognized standards and recommendations on how to execute GNSS surveys, charting operations follow guidelines such as those from the International Hydrographic Organization (IHO; [35.70, 71]).

Surveys in support of *offshore engineering* are similar to construction surveys (Sect. 35.3). Offshore con-

Fig. 35.15 Multibeam sonar used to derive digital elevation model of seabed requires the position and orientation of sonar sensor attached to survey vessel so as to convert range measurements into coordinates of reflecting surface, which may be transformed into electronic nautical charts for navigation or to support offshore engineering (courtesy of Spain Hydrographic Service)

Fig. 35.16 Positioning of offshore cable laying ships and drill platforms is nowadays undertaken using GNSS technology (courtesy of Alf van Beem, after [35.72])

struction applications use identical GNSS surveying instrumentation and techniques to land-engineering surveys. GNSS is used to guide the placement of undersea pipelines or cables (Fig. 35.16), or the erection of offshore structures such as drill platforms, wind or tidal energy generating turbines, or breakwaters, and other river, harbor, or open ocean works. *Dredging*, for example, requires similar technology as does operator guidance of construction machinery (Fig. 35.13), as the objective is to excavate a channel, river, or portion of the seabed to some desired depth.

35.4.2 Operational Issues

There are several unique characteristics of hydrographic surveying worthy of mention. While high-accuracy marine positioning is still based on differential positioning principles, the challenge of operating well offshore, at long distances from GNSS reference stations, means that there is greater interest in using alternative high-accuracy positioning techniques for offshore positioning than is the case on land. Hence the offshore positioning market is an early adopter of PPP techniques, with several service providers transmitting satellite orbit and clock information to support RT-PPP [35.73–76].

Although many hydrographic and charting surveys are carried out near to shore, and even within a harbor, the coordinate datum is in general different to the land geodetic datum. Many offshore engineering surveys use a project datum (as do many onshore engineering projects). The IHO has mandated that the horizontal datum for all charting must be that of WGS84 [35.69, 77] – for all intents and purposes an ITRF-aligned datum. The guidelines for hydrographic surveys also tend to be internationally applicable [35.70, 71]. The RT-GNSS service providers who cater for the offshore surveying market are companies that operate on a global basis.

The seabed map is typically used for ship navigation, hence all underwater or exposed obstacles that pose a danger to maritime shipping should be accurately surveyed. There must be under-keel clearance of the traversing vessel, hence the vertical, or depth accuracy is required to be higher than the horizontal accuracy of any map feature. For all but the largest scale charts this implies a horizontal accuracy of no better than 5–10 m (and often much worse), while the depth accuracy requirement in rivers, harbors, and shipping channels may be at the submeter-level (and often higher). The *chart datum* is typically the Lowest Astronomical Tide [35.78].

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