RTK GNSS Basics

Real Time Kinematic (RTK) satellite navigation is a technique used in land survey and in hydrographic survey based on the use of carrier phase measurements of the GPS, GLONASS, BEIDOU and/or Galileo signals where a single reference station provides the real-time corrections, providing up to centimetre-level accuracy. When referring to GPS in particular, the system is also commonly referred to as **Carrier-Phase Enhancement**, **CPGPS**.

"Normal" satellite navigation receivers compare a pseudorandom signal being sent from the satellite with an internally generated copy of the same signal. Since the signal from the satellite takes time to reach the receiver, the two signals do not "line up" properly; the satellite's copy is delayed in relation to the local copy. By progressively delaying the local copy more and more, the two signals will eventually line up properly. That delay is the time needed for the signal to reach the receiver, and from this the distance from the satellite can be calculated.

The accuracy of the resulting range measurement is generally a function of the ability of the receiver's electronics to accurately compare the two signals. In general receivers are able to align the signals to about 1% of one bit-width. For instance, the coarse-acquisition (C/A) code sent on the GPS system sends a bit every 0.98 microsecond, so a receiver is accurate to 0.01 microsecond, or about 3 metres in terms of distance. The military-only P(Y) signal sent by the same satellites is clocked ten times as fast, so with similar techniques the receiver will be accurate to about 30 cm. Other effects introduce errors much greater than this, and accuracy based on an uncorrected C/A signal is generally about 15 m.

RTK follows the same general concept, but uses the satellite's carrier as its signal, not the messages contained within. The improvement possible using this signal is potentially very high if one continues to assume a 1% accuracy in locking. For instance, the GPS coarse-acquisition (C/A) code broadcast in the L1 signal changes phase at 1.023 MHz, but the L1 carrier itself is 1575.42 MHz, over a thousand times as fast. This frequency corresponds to a wavelength of 19 cm for the L1 signal. Thus a ±1% error in L1 carrier phase measurement corresponds to a ±1.9mm error in baseline estimation.

The difficulty in making an RTK system is properly aligning the signals. The navigation signals are deliberately encoded in order to allow them to be aligned easily, whereas every cycle of the carrier is similar to every other. This makes it extremely difficult to know if you have properly aligned the signals or if they are "off by one" and are thus introducing an error of 20 cm, or a larger multiple of 20 cm. This **integer ambiguity** problem can be addressed to some degree with sophisticated statistical methods that compare the measurements from the C/A signals and by comparing the resulting ranges between multiple satellites. However, none of these methods can reduce this error to zero.

In practice, RTK systems use a single base station receiver and a number of mobile units. The base station re-broadcasts the phase of the carrier that it measured, and the mobile units compare their own phase measurements with the ones received from the base station. There are several ways to transmit a correction signal from base station to mobile station. The most popular way to achieve real-time, low-cost signal transmission is to use a radio modem, typically in the UHF band. In most countries, certain frequencies are allocated specifically for RTK purposes. Most land survey equipment has a built-in UHF band radio modem as a standard option.

This allows the units to calculate their *relative* position to millimetres, although their absolute position is accurate only to the same accuracy as the position of the base station. The typical nominal accuracy for these dual-frequency systems is 1 centimetre ± 2 parts-per-million (ppm) horizontally and 2 centimetres ± 2 ppm vertically.

Although these parameters limit the usefulness of the RTK technique in terms of general navigation, it is perfectly suited to roles like surveying. In this case, the base station is located at a known surveyed location, often a benchmark, and the mobile units can then produce a highly accurate map by taking fixes relative to that point. RTK has also found uses in auto drive/autopilot systems, precision farming and similar roles.

The **Continuously Operating Reference Station** (CORS) method extends the use of RTK to a whole area of a reference station network. Operational reliability and the accuracies to be achieved depend on the density and capabilities of the reference station network.

Code-Phase vs Carrier-Phase

The words "Code-Phase" and "Carrier-Phase" may sound like electronic mumbo-jumbo but, in fact, they just refer to the particular signal that we use for timing measurements. Using the GPS carrier frequency can significantly improve the accuracy of GPS.

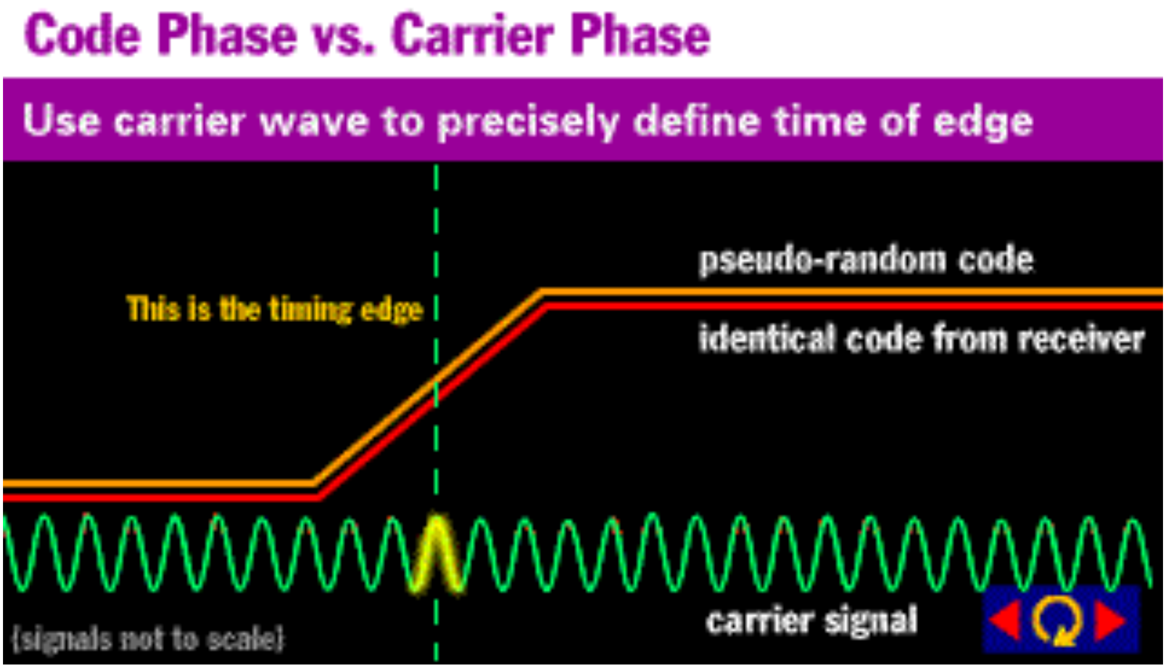
The concept is simple but to understand it let's review a few basic principles of GPS.

Remember that a GPS receiver determines the travel time of a signal from a satellite by comparing the "pseudo random code" it's generating, with an identical code in the signal from the satellite.

The receiver slides its code later and later in time until it syncs up with the satellite's code. The amount it has to slide the code is equal to the signal's travel time.

The problem is that the bits (or cycles) of the pseudo random code are so wide that even if you do get synced up there's still plenty of slop, therefore causing a positioning error. That's the problem with code-phase GPS. It's comparing pseudo random codes that have a cycle width of almost a microsecond. And at the speed of light a microsecond is almost 300 meters of error!

Code-phase GPS isn't really that bad because receiver designers have come up with ways to make sure that the signals are almost perfectly in phase. Good receivers get with in a percent or two. But that's still at least 3-6 meters of error.



Code-Phase vs Carrier-Phase

Survey receivers beat the system by starting with the pseudo random code and then move on to measurements based on the carrier frequency for that code. This carrier frequency is much higher, so its pulses are much closer together and therefore more accurate.

If you're rusty on the subject of carrier frequencies, consider your car radio. When you tune to 94.7 on the dial, you're locking on to a carrier frequency that's 94.7 MHz.

Obviously, we can't hear sounds at 94 million cycles a second. The music we hear is a modulation (or change) in this carrier frequency. So, when you hear someone sing an "A" note on the radio you're actually hearing the 94.7 MHz carrier frequency being varied at a 440-cycle rate.

GPS works in the same way. The pseudo random code has a bit rate of about 1 MHz but its carrier frequency has a cycle rate of over a GHz (which is 1000 times faster!)

At the speed of light, the 1.57 GHz GPS signal has a wavelength of roughly twenty centimetres, so the carrier signal can act as a much more accurate reference than the pseudo random code by itself. And if we can get to within one percent of perfect phase like we do with code-phase receivers we'd have 3 or 4 millimetre accuracy!

In essence this method is counting the exact number of carrier cycles between the satellite and the receiver.

The problem is that the carrier frequency is hard to count because it's so uniform. Every cycle looks like every other. The pseudo random code on the other hand is intentionally complex to make it easier to know which cycle you're looking at.

So, the trick with "carrier-phase GPS" is to use code-phase techniques to get close. If the code measurement can be made accurate to say, a meter, then we only have a few wavelengths of carrier to consider as we try to determine which cycle really marks the edge of our timing pulse.

Resolving this "carrier phase ambiguity" for just a few cycles is a much more tractable problem and as the computers inside the receivers get smarter and smarter it's becoming possible to make this kind of measurement without all the ritual that surveyors go through.

Set Up of RTK System

Real-Time Kinematic (RTK) positioning is positioning that is based on at least two GPS receivers—a base receiver and one or more rover receivers. The base receiver takes measurements from satellites in view and then broadcasts them, together with its location, to the rover receiver(s). The rover receiver also collects measurements to the satellites in view and processes them with the base station data. The rover then estimates its location relative to the base. Typically, base and rover receivers take measurements at regular 1 second epochs (events in time) and produce position solutions at the same rate.

Carrier Phase Initialization

The key to achieving centimeter-level positioning accuracy with RTK is the use of the GPS carrier phase signals. Carrier phase measurements are like precise tape measures from the base and rover antennas to the satellites. In the RTK receiver, carrier phase measurements are made with millimeter-precision. Although carrier phase measurements are highly precise, they contain an unknown bias, termed the *integer cycle ambiguity,* or *carrier phase ambiguity*. The rover RTK receiver has to resolve, or initialize, the carrier phase ambiguities at power-up and every time the satellite signals are interrupted.

The RTK receiver can automatically initialize the carrier phase ambiguities as long as at least five common satellites are being tracked at base and rover sites. *Automatic initialization* is sometimes termed *On-The-Fly (OTF)* or *On-The-Move,* to reflect that no restriction is placed on the motion of the rover receiver throughout the initialization process.

The RTK receiver uses L1 and L2 carrier phase measurements plus precise code range measurements to the satellites to automatically initialize the ambiguities. The initialization process takes between 10 seconds and a few minutes. While the receiver is initializing the ambiguities, it generates a *float* solution with meter-level accuracy. The float solution is reflected in the position display and outputs. When the initialization process is complete, the solution mode switches from float to fix, and the precision changes from meter-level to centimeter-level accuracy.

As long as at least four common satellites are continuously tracked after a successful initialization, the ambiguity initialization process does not have to be repeated.

Tip — Initialization time depends on baseline length, multipath, and prevailing atmospheric errors. To minimize the initialization time, keep reflective objects away from the antennas, and make sure that baseline lengths and differences in elevation between the base and rover sites are as small as possible.

Update Rate and Latency

The number of position fixes delivered by an RTK System per second also defines how closely the trajectory of the rover can be represented and the ease with which position navigation can be accomplished. The number of RTK position fixes generated per second defines the *update rate*. Update rate is quoted in Hertz (Hz). For the Trimble receiver, the maximum update rate is 50 Hz.

Solution latency refers to the lag in time between when the position was valid and when it was displayed. For precise navigation, it is important to have prompt position estimates, not values from 2 seconds ago. Solution latency is particularly important when guiding a moving vehicle. For example, a vehicle traveling at 25 km/h, moves approximately 7 m/s. Thus, to navigate to within 1 m, the solution latency must be less than 1/7 (= 0.14) seconds.

Figure 2.1 contains a summary of the factors contributing to the latency in the synchronized RTK solution.

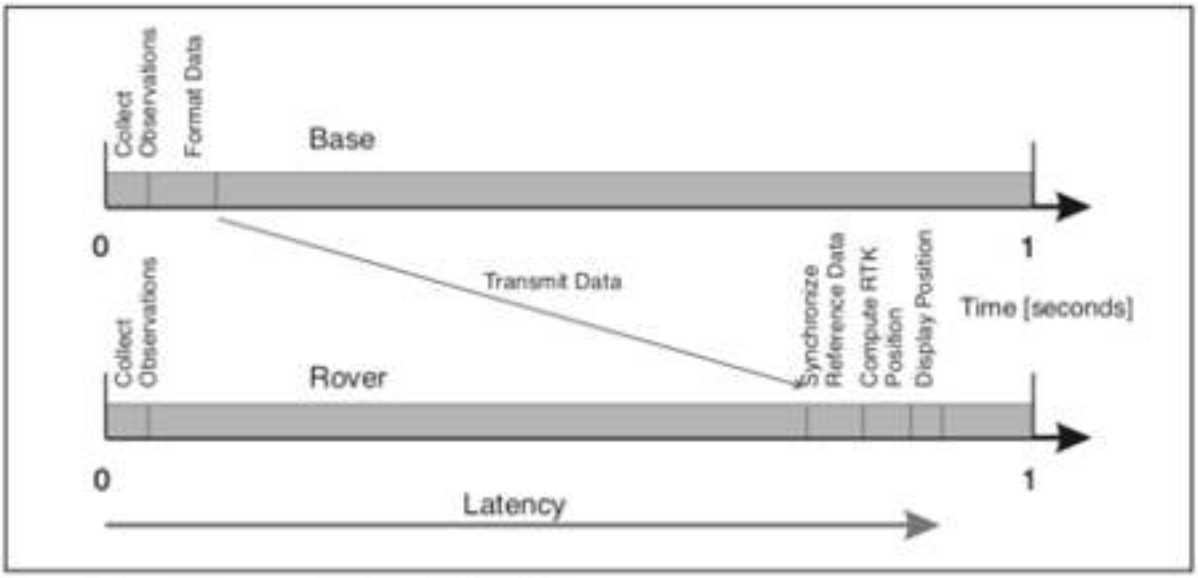


Figure 2.1 Factors contributing to RTK latency

The accumulation of the following parameters can result in a maximum latency of 0.5 to 2 seconds in the RTK solution:

- Base receiver observation collection time
- Reference data formatting
- Data transmission
- Synchronization of base and rover data
- Position calculation
- Solution display/output

Data Link

The base-to-rover data link serves an essential role in an RTK System. The data link must transfer the base receiver carrier phase, code measurements, plus the location and description of the base station, to the rover.

The Trimble RTK receiver supports two data transmission standards for RTK positioning: the Compact Measurement Record (CMR) format and the RTCM/RTK messages. The CMR formal was designed by Trimble and is supported across all Trimble RTK products.

For a detailed description of this standard, see Talbot [1996] and Talbot [1997].

The Radio Technical Commission for Maritime Services (RTCM) developed RTK messages as part of their Version 2.2 standard. For more information, see RTCM [1998].

RTCM/RTK messages 18 to 21 were aimed at forming an industry standard for mixing and matching RTK base and rover systems from different manufacturers.

Industry acceptance of the RTCM/RTK messages has been limited, because the messages require at least a 4800 baud data link, compared with a 2400 baud data link for the CMR format. Furthermore, antenna and receiver compatibility issues have not been completely resolved between RTK manufacturers. Use caution when trying to mix RTK systems from different manufacturers; degraded performance nearly always results.

Not all RTK positioning modes are supported when the RTCM/RTK format is used. Use the CMR format for all Trimble RTK positioning applications.

Factors to consider when choosing a data link include:

- Throughput capacity
- Range
- Duty cycle
- Error checking/correction
- Power consumption

The data link must support at least 4800 baud, and preferably 9600 baud throughput. Step Global can provide you with a range of alternatives that meet these requirements.

RTK Positioning Modes

The RTK receiver should have four positioning modes to support a broad spectrum of user applications. The following section highlights the differences and requirements for each positioning mode.

Synchronized RTK (1 Hz)

Synchronized RTK is the most widely used technique to achieve centimeter-level position estimates between a fixed base station and a roving receiver. Typically, the update rate for Synchronized RTK is once per second (1 Hz). With Synchronized RTK, the rover receiver must wait until the base station measurements are received before computing a baseline vector. The latency of the synchronized position fixes is dominated by the data link delay (see Figure 2.1). Given a 4800 baud data link, the latency of the Synchronized RTK fixes will approach 0.5 seconds. The solution latency could be reduced by using a 9600 baud, or higher bandwidth data link.

The Synchronized RTK solution yields the highest precision possible and suits low dynamic applications such as human-mounted guidance. Airborne applications such as photogrammetry, or aircraft landing system calibration, demand update rates in excess of 1 Hz, to sample the platform trajectory. Data postprocessing can generate the results of the mission back in the office. However, this would require raw GPS data to be stored and postprocessed. Postprocessing presents data management problems, particularly for large data sets collected at 5 or 10 Hz.

Fast Update Synchronized RTK (5 to 10 Hz)

The Fast Update Synchronized RTK scheme has the same latency and precision as the 1 Hz synchronized approach. However, position solutions are generated 5 or 10 times per second (5 or 10 Hz), see Figure 2.2.

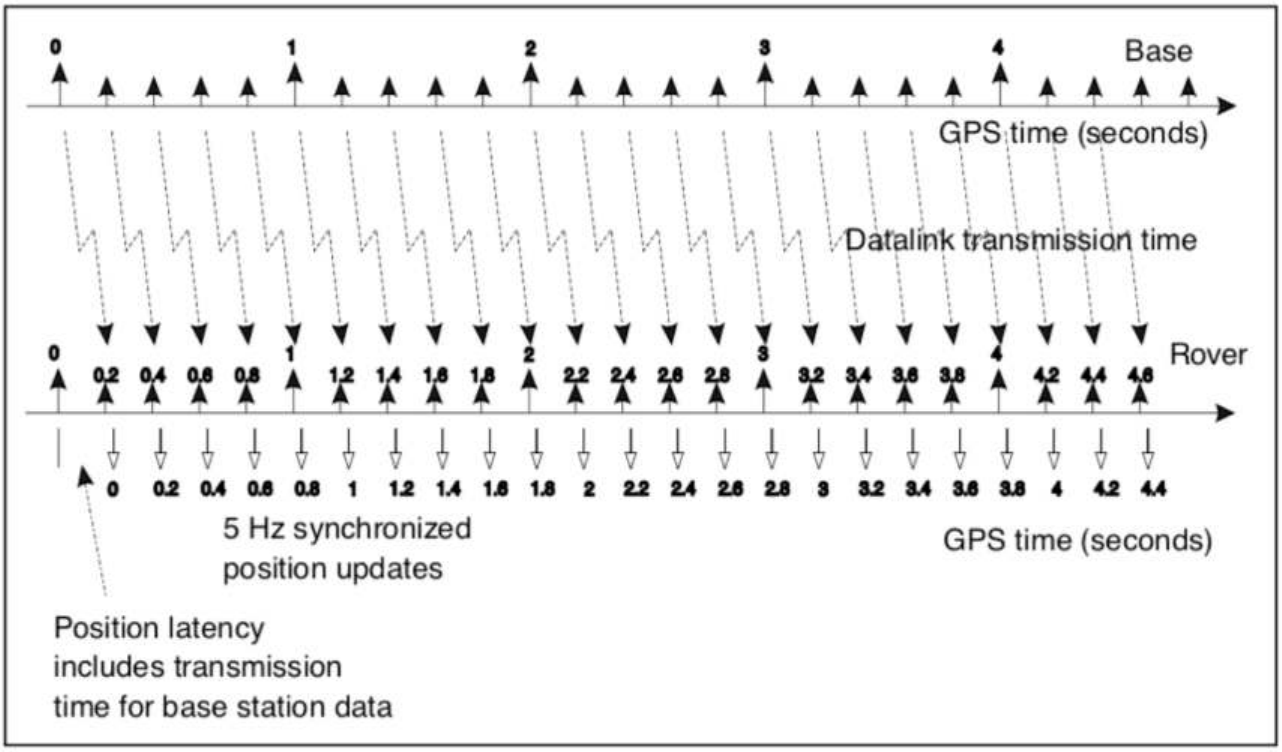


Figure 2.2 Fast update rate synchronized RTK (5 Hz)

The RTK base station must be configured to output CMR data in either the 5 Hz, or 10 Hz CMR Mode. In the Fast Output Mode, the RTK base receiver interleaves the 1 Hz CMR measurement data with highly compressed information at the x.2, x.4, x.6 and x.8 second epochs for 5 Hz output. At the 10 Hz CMR output rate, packets are sent at x.1, x.2, x.3,..., x.9 seconds between the x.0 epochs. The total data throughput requirement for the Fast Mode is less than 9600 bps for 9 satellites.

The RTK rover synchronizes its own 5 or 10 Hz measurements with those received from the base. Results are then generated and can be output at 5 or 10 Hz. The data link throughput is critical to the Operation of the Fast Update Synchronized RTK scheme. Use at least a 9600 baud data link to achieve satisfactory results.

Note — The Fast Update Synchronized RTK mode is only supported through the CMR format. The RTCM messages cannot be output at 5 or 10 Hz.

Low Latency RTK

A large part of the solution latency in Synchronized RTK processing is due to the data formatting and transmission of the base station data to the rover (see Figure 2.1 on page 10). The RTK receiver includes a Low Latency positioning mode for applications that demand centimeter-level accuracy almost instantaneously. The Low Latency positioning mode delivers 20 Hz position fixes with around 20 msec latency with a precision that is only slightly less accurate than Synchronized RTK positioning.

The Low Latency positioning scheme relies on the predictability of the base station phase data. Phase measurements observed at a fixed base receiver generally exhibit a smooth trend. Variations in the carrier phase are caused by:

- Cycle slips
- Satellite motion
- Receiver and satellite clock variations
- Atmospheric delay

Given a brief history of base station phase measurements, the RTK receiver is able to accurately predict what they will be in the next few seconds. Instead of waiting for base station carrier phase measurements to arrive, the RTK rover predicts or projects what the base carrier phase measurements will be for the current epoch. A baseline solution is then generated using the projected base station carrier phase measurements and the observed rover receiver carrier phase. The latency of the position solution derived from projected carrier phase is around 20 milliseconds for the RTK receiver.

With the Low Latency positioning scheme, accuracy is traded for timeliness. An increase in the data link delay relates to an increase in the projection time of the base station phase data. This leads to an increase in the uncertainty of the RTK solution. Figure 2.3 presents an empirically derived model for the base receiver phase projection errors as a function of data link delay.

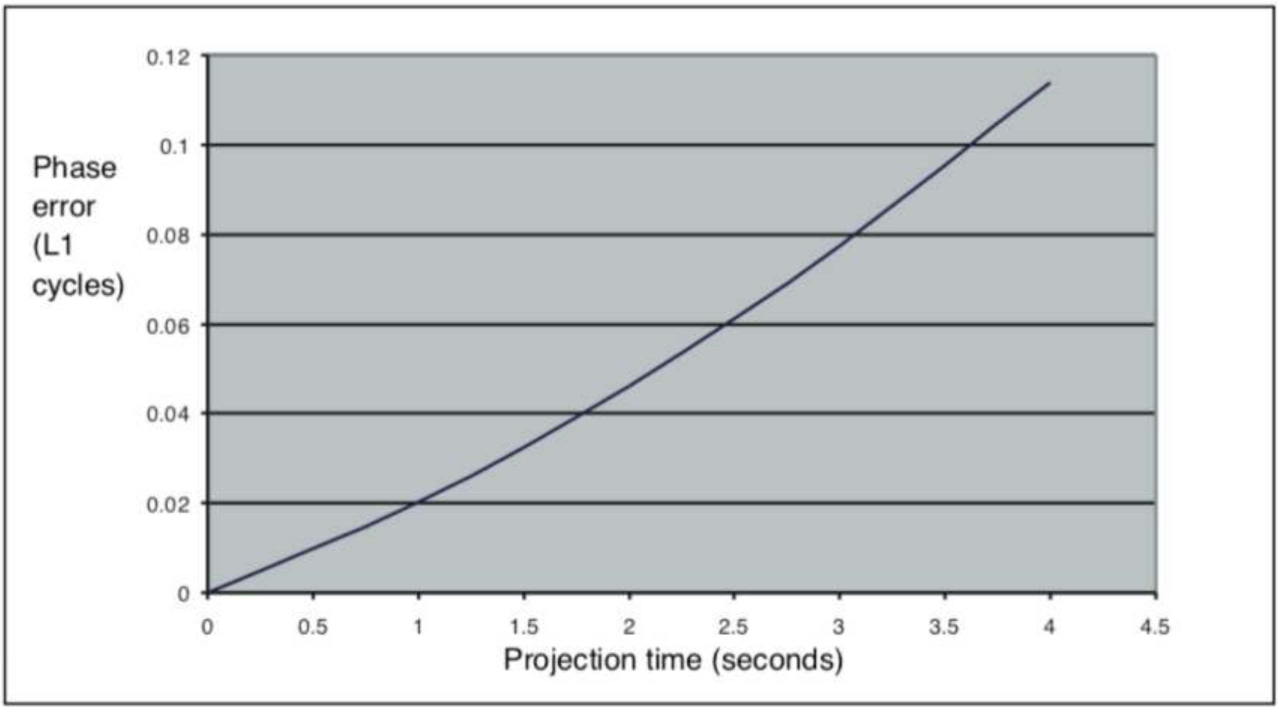


Figure 2.3 Phase projection for the low latency RTK solution

The base phase prediction errors are governed by:

- Unmodeled Selective Availability errors
- Short term instabilities in the receiver and satellite clocks
- Unmodeled satellite orbit variations

A data link latency of 1 second would result in phase projection errors approaching 0.02 cycles (0.004 m). Multiplying the phase projection errors by a PDOP of 3.0 would yield an increase in noise for the Low Latency RTK solution of 3.0 *x* 0.004 = 0.012 m over the Synchronized RTK solution. In many applications the slight noise increase in the Low Latency Solution is tolerable.

Moving Baseline RTK

In most RTK applications, the base station remains stationary at a known location, while the rover moves. A method of RTK positioning, called *Moving Baseline RTK,* is implemented in the Trimble Receivers. Both the base and rover receivers move. The Moving Baseline RTK technique can be used for vehicle orientation applications (see Figure 2.4), and precise relative displacement tracking of two moving vehicles.

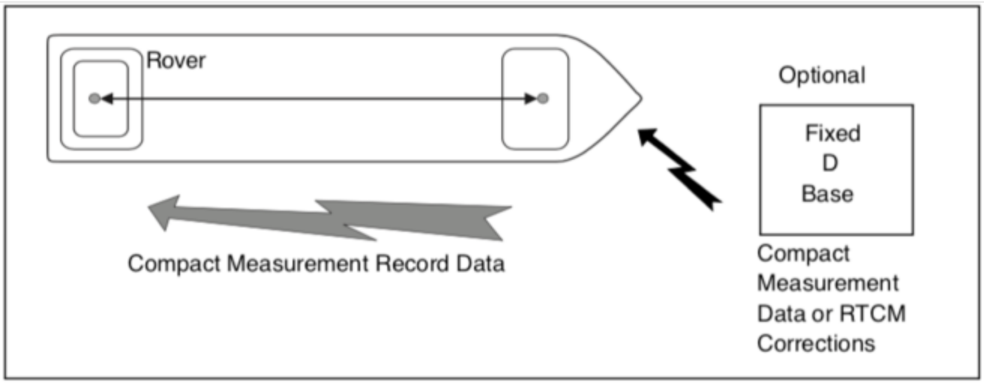


Figure 2.4 Moving baseline RTK applied to ship heading estimation

With the Moving Baseline RTK technique, the base receiver broadcasts CMR measurement and station location data every epoch and the rover receiver performs a synchronized baseline solution at 1, 5, or 10 Hz. The resultant baseline solution is accurate to centimeter-level, while the absolute location of the base—rover space vector is only accurate to 100 m. The accuracy of the derived baseline vector is somewhat dictated by the knowledge of the moving base location. For this reason, the base—rover separation should be less than 1 km to ensure optimal results.

Enhancing Moving Baseline RTK

Although the Moving Baseline RTK mode provides centimeter-level vector components between moving base and rover, the absolute coordinates of the base and rover are only generally known to 100 m. The RTK receiver is capable of performing DGPS or RTK while acting as the moving base station.

Moving base positions are estimated relative to a fixed base to, say, meter-level with DGPS, or centimeter-level with RTK. This technique is best explained with an example. Figure 2.5 shows an example of an application.

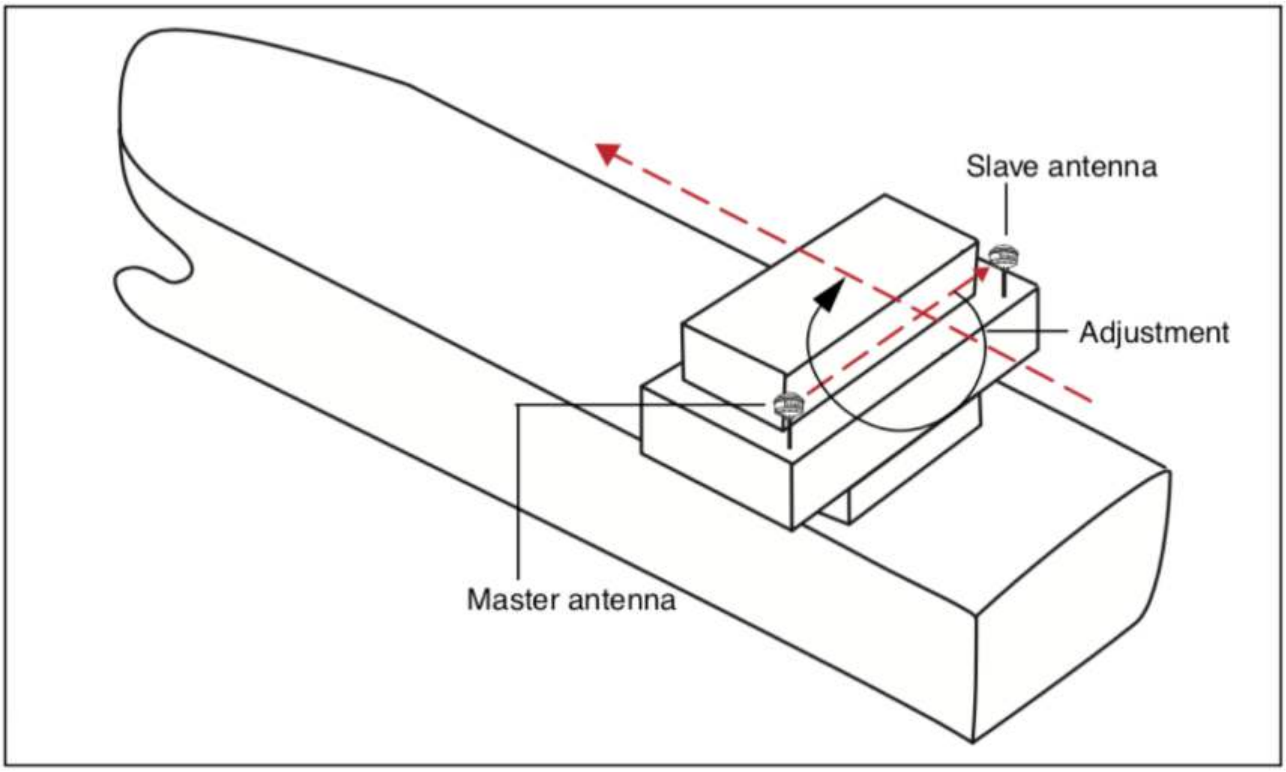


Figure 2.5 Vessel heading from moving baseline RTK

In this example, if the master receiver broadcasts CMR measurement and station location data every epoch, while the slave receiver performs a synchronized baseline solution at, say, 10 Hz, the resultant baseline solution has centimeter-level accuracy while the absolute location of the master/slave space vector is only accurate to 15 m.

The accuracy of the derived baseline vector is restricted to knowing the moving receiver's reference location. For this reason, the reference/rover separation must be less than 1 km.

Similarly, in the example shown in Figure 2.4 on page 17, a shore-based (fixed) base station sends either RTCM or CMR data to the moving base station on a ship.

The moving base station receives differential corrections from the shore-based base station and generates position solutions. The moving base station can be operated in either Low Latency mode or Synchronized mode. CMR data is output by the moving base station to the rover at either 1, 5, or 10 Hz by using the Standard or Fast CMR output modes, respectively.

The rover accepts CMR data from the moving base station and generates an RTK vector solution at the same rate as moving base CMR transmissions. The rover must be configured in the Synchronized mode. The RTK receiver will automatically force the unit into the Synchronized mode if the Low Latency mode is currently active.

When the roving base station is differentially corrected, both the vector displacement and absolute location of the moving baseline are derived.

The moving Baseline RTK mode can *chain* together multiple moving base receivers. Chained-RTK is best explained with an example. Consider a static base station (receiver 1) sending out CMR data at 10 Hz. A moving RTK receiver (receiver 2) receives the CMR data from the static base and estimates its location and then outputs CMR data at a 10 Hz rate. Another moving RTK receiver (receiver 3) receives the CMR data from receiver 2 and performs a synchronized RTK solution. Receiver 3 then generates CMR data for transmission to yet another RTK receiver and so on. The solution latency for the last receiver is the summation of the transmission delays of the previous links in the chain. The technique is therefore limited by the data link throughput. The Chained RTK mode can determine the location and orientation of large structures such as bridge elements as they are being moved into position.

Summary of RTK positioning modes

Table 2.1 provides a summary of the RTK positioning modes available in a RTK receiver.

Table 2.1 Characterization of RTK positioning modes

RTK mode	Update rate (Hz)	Latency (seconds)	Data link requirement[1] (Baud)	Accuracy[2]
Synchronized	1	0.5 — 2.5[3]	2400	Horizontal: 1 cm + 2 ppm Vertical: 2 cm + 2 ppm
Fast Update Synchronized	5 or 10	0.5 — 2.5[3]	9600	Horizontal: 1 cm + 2 ppm Vertical: 2 cm + 2 ppm
Low Latency	20 (max)	0.02	2400	Horizontal: 2 cm + 2 ppm[4] Vertical: 3 cm + 2 ppm
Moving Baseline RTK	1, 5, 10	0.5 — 2.5[3]	4800, 9600	Horizontal: 1 cm[5] Vertical: 2 cm

[1] Minimum bandwidth requirement — higher bandwidths provide increased performance

[2] Accuracy figures are 1 sigma

[3] Latency is dependent on data link throughput

[4] Accuracy figures assume a 1 second data link delay

[5] Assumes that base — rover separation is less than 1 km

Critical Factors Affecting RTK Accuracy

The following sections present System limitations and potential problems that could be encountered during RTK Operation.

Base station receiver type

Caution — Trimble recommends that you always use a Trimble base station with a Trimble rover. Using a non-Trimble base receiver can result in suboptimal initialization reliability and **RTK** performance.

The Trimble receiver uses a state-of-the-art tracking scheme to collect satellite measurements. Optimal RTK performance is achieved when using Trimble receivers at base and rover sites. The Trimble receiver is compatible with all other Trimble RTK-capable systems. However, not all RTK positioning modes are supported with mixed receiver Operation.

Base station coordinate accuracy

The base station coordinates used for RTK positioning are set through the *Base Station Control* menu. The base station coordinates should be known to within 10 m in the WGS-84 datum for optimal System Operation. Incorrect or inaccurate base station coordinates degrade the rover position solution. It is estimated that every 10 m of error in the base station coordinates introduces one part per million error in the baseline vector. This means that if the base station coordinates have a height error of 50 m, and the baseline vector is 10 km, then the error in the rover location is approximately 5 cm. One second of latitude represents approximately 31 m on the earth surface; therefore, a latitude error of 0.3 seconds equals a 10 m error on the earth's surface. If the baseline vector is 10 km, then the error in the rover location is approximately 1 cm.

The second effect of base station coordinate errors is on the low latency RTK solutions. With low latency positioning, the baseline vector errors will ramp up with increased data link age.

For Moving Baseline RTK, the base station coordinates are only determined with 10-20 m accuracy with selective availability (S/A) turned off. For this reason, Moving Baseline RTK works best when base-to-rover separation is less than 1 km.

Number of visible satellites

A GPS position fix is similar to a distance resection. Satellite geometry directly impacts on the quality of the position solution estimated by the receiver. The Global Positioning System is designed so that at least 5 satellites are above the local horizon at all times. For many times throughout the day, as many as 8 or more satellites might be above the horizon. Because the satellites are orbiting, satellite geometry changes during the day, but repeats from day-to-day. A minimum of 4 satellites are required to estimate user location and time. If more than 4 satellites are tracked, then an overdetermined solution is performed, and the solution reliability can be measured. The more satellites, the greater the solution quality and integrity.

The Position Dilution of Precision (PDOP) provides a measure of the prevailing satellite geometry. Low PDOP values, in the range of 4.0 or less, indicate good satellite geometry, whereas a PDOP greater than 7.0 indicates that satellite geometry is weak.

Even though only 4 satellites are needed to form a three-dimensional position fix, RTK initialization demands that at least 5 common satellites must be tracked at base and rover sites. Furthermore, Ll and L2 carrier phase data must be tracked on the 5 common satellites for successful RTK initialization. Once initialization has been gained a minimum of 4 continuously tracked satellites must be maintained to produce an RTK solution.

Elevation mask

The elevation mask stops the receiver from using satellites that are low on the horizon. Atmospheric errors and signal multipath are largest for low elevation satellites. Rather than attempting to use all satellites in view, the receiver uses a default elevation mask of 13 degrees. By using a lower elevation mask, System performance may be degraded.

Environmental factors

Environmental factors that impact GPS measurement quality include:

- Ionospheric activity
- Tropospheric activity
- Signal obstructions
- Multipath
- Radio interference

High ionospheric activity can cause rapid changes in the GPS signal delay, even between receivers a few kilometers apart. Equatorial and polar regions of the earth can be affected by ionospheric activity. Periods of high solar activity can therefore have a significant effect on RTK initialization times and RTK availability.

The region of the atmosphere up to about 50 km is called the troposphere. The troposphere causes a delay in the GPS signals which varies with height above sea level, prevailing weather conditions, and satellite elevation angle. The receiver includes a tropospheric model which attempts to reduce the impact of the tropospheric error. If possible, try to locate the base Station of approximately the same elevation as the rover.

Signal obstructions limit the number of visible satellites and can also induce signal multipath. Flat metallic objects located near the antenna can cause signal reflection before reception at the GPS antenna. For phase measurements and RTK positioning, multipath errors are about 1 to 5 cm. Multipath errors tend to average out when the roving antenna is moving while a static base station may experience very slowly changing biases. If possible, locate the base station in a clear environment with an open view of the sky. If possible, use an antenna with a ground plane to help minimize multipath.

The RTK receiver provides good radio interference rejection. However, a radio or radar emission directed at the GPS antenna can cause serious degradation in signal quality or complete loss of signal tracking. Do not locate the base station in an area where radio transmission interference can become a problem.

Operating Range

Operating range refers to the maximum separation between base and rover sites. Often the characteristics of the data link determine the RTK operating range. The initialization performance of the Trimble receiver is optimized for an operating range up to 20 km. Degraded initialization time and reliability are likely to result if RTK is attempted beyond the 20 km operating range specification.