GPStation6 GISTM Receiver
TEC Estimation and Calibration

1 Purpose and Scope

The purpose of this document is to describe the TEC estimation and calibration feature supported by GPStation6 receiver. The scope is limited to generic description and does not provide implementation specific details.

The document content is relevant to, and supplements, Section 2.7 TEC Calibration in the GPStation-6 GNSS Ionospheric Scintillation and TEC Monitor (GISTM) Receiver User Manual (OM-20000132).

2 Total Electron Content (TEC)

2.1 TEC Measurement

The Global Navigation Satellite System (GNSS) ranging code and carrier are affected differently as the signal interacts with free electrons, along its transmission path through the ionosphere. The free electrons in the ionosphere advance the GNSS carrier wave (by increasing phase velocity), while retarding the code modulation (by reducing the group velocity). As a result, the range obtained from the integrated carrier phase is shortened while the measurement obtained from the code ranging is lengthened.

The magnitude of the ionospheric delay is a function of the refractive index of the ionosphere in the path of the GNSS signal. The refractive index is a function of the transmission center frequency and the total electron content (TEC). The ionospheric delay depends on the number of free electrons present between GNSS receiver and satellite along the line of sight (LOS).

$$-\delta_p = \delta_g = \frac{40.3}{f_c^2} TEC \quad \text{(metres)} \tag{1}$$

Where δ_p and δ_g are the phase (carrier) and group (code) delays. TEC is the integrated electron density along the LOS path and is the total number of electrons per square metre. f_c is the center frequency of GNSS RF signal.

The ionospheric delay is a function of TEC unit (TECU) and operating frequency. For example, 1 TECU will introduce a pseudorange delay of 0.163 metres and 0.267 metres in L1 and L2 frequencies respectively. Conversely, 1 ns of differential delay (between L1 and L2) corresponds to 2.852 TECU.

2.2 Code and Carrier TEC

The carrier derived (integrated Doppler) TEC can be determined from the corresponding L1 and L2 carrier phase observables as,

$$TEC_{\phi} = \frac{-\phi_{L1}+\phi_{L2}}{0.104m\,TECU^{-1}} \tag{2}$$

Where ϕ_{L1} and $\phi_{L2}$are the carrier phase observables of the respective signals. TEC is the column density of electrons measured in TEC units (TECU) (1 TECU = 10^{16} electrons/m^2). TEC derived from carrier phase measurements (carrier tracking) are less noisy compared to code derived TEC. Nevertheless, the carrier derived TEC are limited due to the inherent ambiguity in carrier cycles. Carrier phase derived TEC measurements are also sensitive to cycle slips within carrier phase tracking. Note that the carrier phase derived TEC can still be used for relative change in TEC. GPStation6 does not provide TEC derived from carrier phase. However, it does provide delta TEC (TEC variation) that is derived from carrier phase measurement differences between frequencies.

The code derived (pseudorange) TEC can be determined from the corresponding L1 and L2 pseudorange observables as,

$$TEC_{L1Lx} = \frac{1}{40.3}\left[\frac{f_{L1}f_{Lx}}{f_{L1}-f_{Lx}}\right][PR_{Lx} - PR_{L1}] \tag{3}$$

where f_{L1} is the primary L1 frequency and f_{Lx} is the frequency of the secondary signal. PR_{L1} and PR_{Lx} are the primary and secondary signal pseudorange in metres. TEC derived from code (pseudorange) measurements are noisier compared to carrier TEC but are absolute measurements as they are free from any integer ambiguity. Traditional noise reduction approaches includes limiting the code tracking loop bandwidth (i.e. narrow DLL loop bandwidth) with the aid of carrier tracking or smoothing (i.e. filtering) of code measurements using carrier phase measurements (i.e. Hatch filtering).

2.3 Slant and Vertical TEC

The TEC indicates the total number of free electrons within the ionosphere along the LOS path between the satellite and the receiver. This measurement is often represented as slant TEC (TEC_{sl}) values. To determine the TEC value for different elevation angles, the slant TEC must be translated to vertical TEC (TEC_v). Using a modified single layer model (MSLM) for the ionosphere, the vertical TEC can be obtained from the slant TEC and vice-versa as:

$$M(\epsilon) = \frac{TEC_v}{TEC_{sl}} = \left[1 - \left(\frac{R_e cos(\epsilon)}{R_e + h_{sp}}\right)^2\right]^{\frac{1}{2}} \tag{4}$$

where R_e is the mean radius of Earth, ϵ is the elevation angle, and h_{sp} is the mean height of the ionosphere layer, which is usually taken between 350 and 450 km. Typical values for R_e and h_{sp} are set to 6371 and 450 km respectively.

Further improvements can be achieved by using a multi-shell model instead of single shell model and using appropriate basis functions. For example, JPL ionospheric TEC estimation uses a three shell model with different mean ionospheric heights [TEC5].

2.4 Absolute TEC Measurement

As discussed in Section 2.2, the TEC values derived from carrier phase measurements are limited by the inherent ambiguity in the number of cycles (unknown initialization of carrier phase) and cycle slips. While code derived TEC is not limited by the above, it is still impacted by the satellite and receiver instrument delays and errors. Thus, to get absolute TEC value, these biases must be removed and errors must be reduced. A generic expression of code TEC measurement can be expressed as,

$$TEC_{L1Lx} = TEC_{Abs} + \delta_{SV}^{diff} + \delta_{Rec}^{diff} + \epsilon_{MP} + \epsilon_{noise} \tag{5}$$

where TEC_{Abs} is the absolute TEC value, δ_{SV}^{diff} and δ_{Rec}^{diff} are the differential (inter-frequency) biases within the satellite and the receiver. ϵ_{MP} and ϵ_{noise} are errors caused by the presence of multipath and background noise (i.e. thermal, interference).

2.5 GPStation6 TEC Measurement

GPStation6 provides both the raw and smoothed TEC measurements that are derived from pseudorange. The ISMRAWTEC log contains the raw TEC measurements without any kind of carrier smoothing (See Section 5.1.4 in OM-20000132). The use of ultra-stable oven-controlled crystal oscillator (OCXO) and the narrow delay locked loop (DLL) bandwidths (BW) greatly reduces the noise contribution in raw TEC measurements. Moreover, GPStation6 provides carrier smoothed code TEC measurements as part of the ISMREDTEC log (See Section 5.1.6 in OM-20000132). The ISMREDTEC log contains both smoothed code TEC measurements and delta TEC measurements that are derived from carrier phase. The use of carrier smoothing further reduces the noise in the code TEC measurements.

Table 2-1 lists the different signal combinations for which TEC measurement are reported within GPStation6.

Table 2-1: GPStation6 supported signal combinations for TEC measurement

Signal Combination	Primary Signal	Secondary Signal	Satellite DCB Bias
GPSL1CAL2Y	GPS L1 C/A	GPS L2P(Y)	Known (All PRNs)
GLOL1CAL2P	GLONASS L1C/A	GLONASS L2P	Unknown
GPSL1CAL2C	GPS L1 C/A	GPS L2C	Known (Selected PRNs)
GPSL1CAL5	GPS L1 C/A	GPS L5	Unknown
SBASL1CAL5	SBAS L1 C/A	SBAS L5	Unknown
GLOL1CAL2CA	GLONASS L1 C/A	GLONASS L2 C/A	Unknown

TEC measurements derived from the combination of GPS L1 C/A, L2C and L5 are less noisy and smaller bias from satellite hardware. TEC measurements derived from L2P(Y) in combination with other signals (i.e. L1 C/A) slightly higher probability of error due to the semi-codeless of L2 P(Y) signal. However, for GPSL1CAL2Y signal combination, the satellite differential code biases can be nearly eliminated (See Section 3.1.2) and thus may produce the most accurate TEC estimates. Note that the L2P(Y) tracking is achieved with aiding from L1 C/A. Therefore, the biases associated with L1C/A should be considered when calibrating for the offset.

Unlike GPS signals, the GLONASS legacy signals uses frequency division multiple access (FDMA) spread spectrum modulation, which introduces additional interfrequency biases. Also, the pseudorange accuracy of GLONASS signals is slightly less compared to that of GPS signals. Thus, the measured TEC from GLONASS signals will likely have larger bias and higher probability of error.

TEC measurement is now possible with SBAS with the launch of second frequency at L5. The primary purpose for SBAS is for integrity and augmentation although it can be used for ranging purposes. SBAS does offer a benefit over GNSS systems as the signals are broadcast from Geostationary Orbit (GEO) satellites. Unlike GNSS, the SBAS systems such as WAAS and GAGAN use the bent-pipe architecture. In the bent-pipe architecture, the SBAS signals are generated in ground-based uplink station and is simply broadcasted (after frequency translation) through commercial communication satellites. The coherency between code and carrier are monitored and controlled in a closed loop. Therefore, the TEC derived from SBAS signal combinations will have higher probability of errors. Moreover, due to the inherent biases in the ground uplink station and satellite hardware, the biases will be significantly large compared to GPS and GLONASS systems. In addition, these biases tend to vary markedly compared to GNSS systems.

3 TEC Calibration – Errors & Biases

As with any TEC estimation, the GPStation6 receiver uses the geometry free linear combination of pseudorange observables because all geometry related errors are cancelled. Table 3-1 classifies the geometry related error sources and uncorrelated error sources in regards to geometry free linear combination.

Table 3-1: Geometry free linear combination and error sources

Correlated Error Sources (Geometry Related)	Uncorrelated Error Sources
- Geometric Range - Satellite clock - Receiver clock - Tropospheric delay - Common path delays (antenna, RF cable, receiver RF/IF section) - Relativistic Effects (Sagnac effect)	- Measurement noise (background noise, multipath, and group delay variations) - Satellite specific differential code bias - Receiver differential code bias (antenna, RF cable, receiver RF/IF section) - Ionospheric fluctuations (from model)

3.1.1 Measurement Noise

The background noise originating from the receiver thermal and other interference sources degrade the signal (i.e. C/No) resulting in degraded pseudorange measurements. The presence of multipath results in code tracking error, as the receiver correlates the sum of both direct (LOS) and delayed multipath signal.

More importantly, the error contribution from ϵ_{MP} and that of ϵ_{noise} is amplified (i.e. doubled) due to the combination of pseudorange from different frequencies. Therefore, measurements noises can potentially degrade the accuracy with which the TEC is measured.

The use of narrow DLL bandwidth and carrier smoothing significantly reduces the noise contribution. GPStation6 uses a wider front-end bandwidth of 20 MHz and Pulse Aperture Correlator (PAC) technology that significantly reduces the multipath error. The PAC correlator susceptibility peaks at about 0.05 chips (about 5 m) and reduces negligibly after 0.1 chip.

Finally, the GNSS antenna and RF cable are exposed to environmental conditions and can be impacted by variations in differential group delay (i.e. group delay variations of individual frequencies) caused by:

- Temperature,
- Humidity,
- Air Pressure,
- Mechanical Strain,
- Aging,
- Mismatch (Termination)
- Supply voltage,
- Signal power levels (i.e. dynamic range)

3.1.2 Satellite Differential Code Bias

GPStation6 measures the TEC by differencing the pseudorange measurements between signals from different frequencies (i.e. L1 C/A and L2P(Y)). The code phase between different RF signals at different frequencies has biases from satellite hardware (i.e. up-conversion, filtering). These differential code biases (DCB) are specific to a satellite and vary over the life span of the satellite.

Unlike traditional receivers that use cross-correlation (between L1 P(Y) and L2 P(Y)) to track L2 P(Y), the GPStation6 uses the advanced l2 P(Y) tracking (i.e. Z-tracking). The receiver uses the L1 C/A tracking for aiding L2 P(Y) tracking. Thus, the P2 (L2 P(Y)) code measurement is associated with C1 (C/A code) and not P1 (L1 P(Y)). Hence, the differential code bias associated with P1C1 must be used to get consistent measurements.

GPStation6 allows the user to enter the GPS satellite specific differential code biases (for 32 satellites) that will be used internally within TEC calculation:

- C1P1 (between L1 C/A and L1 P(Y)), which is required for L1 C/A and L2 P(Y) differential TEC estimation
- C2P2 (between L1C/A and L2C), which is required for L1C/A and L2C differential TEC estimation

See Section 4.2.8 SETDIFFCODEBIASES (OM-20000132) command for further details. The bias correction can be applied to the C1P1 combination or C2P2 combination by setting them appropriately in the "Code Pair" field.

Monthly mean values of GPS satellite specific corrections for GPS C1P1 and C2P2 are reported by the Centre for Orbit Determination in Europe (CODE) (ref: ftp://ftp.unibe.ch/aiub/CODE/). Note that C2P2 bias is associated with the GPS IIR-M satellites broadcasting modernized GPS L2C signal. Currently, the biases are not reported by CODE but are expected in the future.

The SETDIFFCODEBIASES command is only applicable to C1P1 and C2P2 biases which are used in L1 C/A-L2P(Y) and L1 C/A-L2C combinations. For all other signal combinations, there satellite specific differential code biases will be present in the computed TEC value.

3.1.3 Receiver Differential Code Bias

As with any GNSS receiver, the GNSS RF signals propagate through a common path before satellite specific processing (i.e. correlation, PSR/ADR measurement). These delays are common to all SV signals for a specific frequency and manifest in the clock offset computation. However, the group delays differ between frequencies and manifest as a bias on the geometry free linear combination. The following components contribute to the difference in group delays between frequencies on the receiver side:

- GNSS Antenna (LNA, Band-pass filtering)
- GNSS Receiver (LNA, RF/IF Filtering)

Note that the RF cable is not included as they have a broadband frequency response resulting in constant group delays across the GNSS operating frequency range.

The differential group delay (between L1 and L2) for some geodetic range antennas is summarized in Table 3-2 . It is obvious that the group delay difference can introduce significant bias in TEC measurement if not compensated.

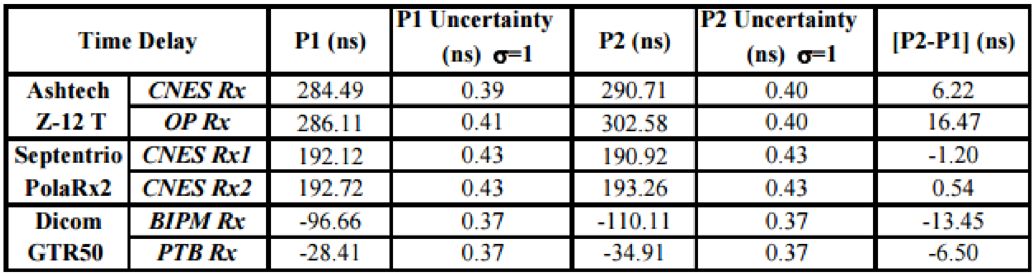
Table 3-2: Reported Differential Group Delay for GNSS Antennas

Antenna Model	Frequency Band	Differential Group Delay (ns)
NovAtel GNSS 750	Upper: 1525-1612 MHz Lower: 1164 -1301 MHz	9 (~ 25 TECU)
NovAtel GPS 702 GG NovAtel GPS 703 GGG	L1: 1588.5 ± 23 MHz L2: 1236 ± 18.3 MHz	5 (~ 14 TECU)

It is expected that the antenna phase center variation (PCV) can also introduce azimuth/elevation specific additional bias. However, for geodetic antennas the variation is expected to be less than 1 cm.

Table 3-3 lists the measured differential delays (between L1 and L2, see [P2-P1] column) for a few GNSS receivers. The authors [TEC7] reported that the measured differential delay varied between individual units of the same receiver type. Again, it can be seen that the receiver RF/IF differential delay can introduce significant bias in estimated TEC if not compensated.

Table 3-3: Measured group delay for different GNSS receivers (ref: [TEC7])



Time Delay		P1 (ns)	P1 Uncertainty (ns) σ=1	P2 (ns)	P2 Uncertainty (ns) σ=1	[P2-P1] (ns)
Ashtech Z-12 T	***CNES Rx***	284.49	0.39	290.71	0.40	6.22
	OP Rx	286.11	0.41	302.58	0.40	16.47
Septentrio PolaRx2	***CNES Rx1***	192.12	0.43	190.92	0.43	-1.20
	CNES Rx2	192.72	0.43	193.26	0.43	0.54
Dicom GTR50	***BIPM Rx***	-96.66	0.37	-110.11	0.37	-13.45
	PTB Rx	-28.41	0.37	-34.91	0.37	-6.50

For GPStation6, the differential bias between L1 and L2 delays are internally corrected using a predefined value. This ensures that receiver bias contribution to TEC estimate is minimal. However, it is expected that some residual bias due to unit-to-unit variation may exist.

3.1.4 Ionospheric Fluctuations

While independent calibration of the receiver (antenna, cable and receiver) is possible, it introduces significant difficulty in site deployment. Besides, absolute calibration of antenna, cable and receiver requires a special chamber (anechoic) and calibrated signal transmission to accurately measure the delay. Therefore, traditional approaches use the site specific setup and measure the differential code biases along with ionospheric delays by collecting TEC data. Subsequently, the contribution from ionosphere is removed to obtain the combined satellite/receiver specific DCB.

The TEC data are first obtained over the calibration period, which includes the contribution from satellite/receiver specific DCBs and that of ionosphere. Simpler methods to obtain the receiver/satellite differential code biases are to assume TEC of about 3-5 TECU at vertical nighttime data (quiet ionosphere). Alternatively, the ionospheric delay predicted from an independent model (i.e. thin shell single layer) can be used to remove the contribution from ionosphere to determine the satellite/receiver code bias. This approach eliminates the need for complicated receiver calibration but its accuracy depends on the underlying model used for TEC prediction.

4 GPStation6 TEC Calibration Guideline

4.1 Site Setup Check

The following are generic recommendations to ensure that site deployment minimizes the contributions from various error/bias sources during TEC calibration and receiver operation:

Site Survey

The GNSS receiver antenna must have a clear open sky view of at least 100 metres to the horizon across all azimuth angles.

Verify that there are no nearby interference sources for at least 300 metres.

Verify that there are no nearby signal reflectors such as standing water surfaces, flat metal surfaces, wire fences, large areas of glass, or concrete paving.

Verify the antenna, mount, and RF cable are supported properly. Weather proof (i.e. radome) the antenna to limit the impact of solar heating and other environmental factors.

RF Signal Calibration

To ensure optimal receiver operation, the RF input power level to the receiver should be within the linear operating range of the receiver. Perform a link budget of the setup to determine the expected RF input levels and select the antenna and cable length accordingly. After antenna and cable setup, measure the RF input level again to confirm that is within the receiver operating range (preferably in the middle). This can be further verified by observing the RF AGC out of Range Bit (Nibble 4 and 5) within the RXSTATUS log (See RXSTATUS log in OM-20000132).

Ensure the RF cable connectors are properly impedance matched (i.e. 50 ohm).

Antenna Power

Ensure that antenna is powered if it is an active antenna (see ANTENNAPOWER command in OM-20000132)

4.2 GPStation6 Auto Calibration

The GPStation6 auto calibration feature allows the user to carry out TEC calibration to compensate for the instrumental biases easily using the existing site setup. If the satellite specific differential code bias is unknown or not entered, the auto-calibration lumps the satellite biases with that of receiver during calibration.

GPStation6 uses a proprietary TEC model to remove the contribution of ionosphere from the estimated TEC and thus provides the receiver (antenna and GNSS receiver) associated DCBs. It further improves the accuracy by averaging the TEC values computed using different satellites (by mapping in to Vertical TEC).

As part of self-calibration, GPStation6 allows the user to specify the following auto calibration specific parameters (see Section 4.2.4 ISMCALIBRATE in OM-20000132):

- Binary flag (enable/disable) to start and end the calibration.
- Delayed start for calibration (0 to 604800) in seconds
- Calibration duration (0 to 604800)
- Elevation Cutoff angle (± 90) in degrees that will be used to include the satellite TEC data. TEC data from satellites whose elevation is higher will be used for TEC calibration
    - While elevation cutoff limits the number of satellites used for TEC calibration, it greatly reduces the error from using TEC data of lower elevation angles.

The receiver DCB’s are reported in the ISMCALIBRATIONSTATUS log (See Section 5.1.7 in OM-20000132). The log contains the following:

- Calibration period (duration in seconds)
- For each signal combination type (see Table 20 in OM-20000132)
    - Number of samples used for TEC calibration
    - TEC calibration value in TECU
    - Standard deviation of the TEC calibration in TECU

GPStation6 auto calibration does not automatically apply the satellite and receiver DCB’s. This should be entered as part of receiver start up (see ISMTECCALIBRATION).

The following sections outline procedures and steps to improve the accuracy of the GPStation6 auto calibration.

4.2.1 Calibration Period

The calibration period depends on the start time, end time and the duration over which the calibration is performed. The ideal period for auto calibration is when:

- minimum TEC occurs, and
- there is minimal TEC variation over the calibration duration
- the maximum number of satellites are above the elevation cut-off angle

While the ionospheric activity is minimal during the night time (i.e. between 4:00 and 6:00 HRS local time), it is strongly recommended to collect relative TEC and Scintillation data during the preselected period and confirm it is the TEC minimum (albeit relative) and there is negligible scintillation (S4 and sigma phi). This can be repeated over few days to ensure that day-to-day variation is minimal.

The GPStation6 auto calibration allows user to enter an elevation cutoff angle to include only satellites with clean TEC data. Hence, it is desirable to select the days where maximum number of satellites will be available during the calibration period.

4.2.2 Correcting for Satellite DCBs

As discussed in Section 3.1.2, the GPStation6 allows user to enter the GPS satellite specific DCBs. This ensures that the GPS SV specific DCB's are accounted for independently of calibration and are thereby improving the TEC calibration accuracy.

Note that the SV DCBs are entered as nanoseconds for the 32 GPS SV with remaining set to 0.0. More importantly, these values should be used subsequently during operation until another calibration is performed or when it is updated (see monthly CODE C1P1 data available from: ftp://ftp.unibe.ch/aiub/CODE/).

4.2.3 Self-Calibration

- At the start of calibration period, ensure that satellite specific DCBs are applied
- Example: SETDIFFCODEBIASES gps_c1p1 -0.207 -0.043 1.0123 …. (40 values)
- Commence self-calibration (ISMCALIBRATE)
    - Set start (enable) and duration of calibration
    - Set elevation cutoff. It is strongly recommended to set the elevation angle is high as possible (i.e. greater than 65 degrees).
    - Example: ISMCALIBRATE enable 3600 7200 65
- Log the calibration status
    - Example: LOG ISMCALIBRATIONSTATUS ONNEWs
- The following logs provide useful information when investigation issues with self-calibration data (See OM-20000132):
    - ISMREDTECB
    - ISMREDOBSB
    - RXSTATUS
    - RANGE, and
    - CLOCKMODEL/CLOCKSTEERING.

4.3 Post-calibration analysis

Once calibration is done, it is recommended to review the quality of the calibration by analyzing the TEC data of the satellites that were above the elevation cutoff. This includes:

- the number of samples used for TEC calibration
- the standard deviation of TEC estimates
- the relative TEC and Delta TEC (from ISMREDTEC)
- the average CMC, CMC standard deviation, S4 and sigma phi from ISMREDOBS

If the previous calibration result is available, compare any differences between the current calibration and the previous one.

It is strongly recommended to perform the self-calibration over a few days (3 – 5 days) using the same calibration setting. The average across these estimates can be used as the final calibration offsets. Note that the standard deviation computed from different TEC calibration tests will provide a good indication on the accuracy of the self-calibration.

4.4 Using Auto Calibration Offsets

The GPStation6 does not apply the auto calibration offsets or the satellite specific DCBs. The user should enter the following as part of receiver start up:

- The satellite specific DCBs from the CODE P1C1 data base should be applied
    - Example: SETDIFFCODEBIASES gps_c1p1 -0.207 -0.043 1.0123 …. (40 values)
- The TEC calibration offsets for different signal combination should be applied
    - Example: ISMTECCALIBRATION gpsl1caL2Y -12.25

      ISMTECCALIBRATION gpsl1cal2c -13.45
- Save the calibration offsets within the receiver nonvolatile memory (NVM) using the SAVECONFIG command (see OM-20000132) so that the TEC offsets will be used by default at start-up
    - Example: SAVECONFIG

4.5 Generic Error Budget

Table 4-1 summarizes the expected accuracy of code derived TEC with and without calibration. The TEC accuracy is greatly impacted by the unknown biases in the satellite, antenna and, the GNSS receiver.

GPstation-6 HW uses predefined calibration offset to compensate for the inherent RF/IF hardware delays.

The GPstation6 auto-calibration feature is expected to provide the most accurate calibration for the GPS L1C/A and the L2P(Y) signal combination, when satellite specific DCBs are used. For other signal combinations, the satellite specific differential code biases are unknown and thus lumped with the receiver DCBs during calibration. As the calibration is based on a limited number of satellites that are visible and used for TEC calibration, the accuracy of TEC calibration may still be impacted by the variation in DCBs on the satellite side. Hence, it is better to repeat the TEC calibration for multiple days to maximize the number of satellites used for TEC calibration.

Table 4-1: Example TEC Biases before and after calibration

Component	TEC Accuracy (TECU)	
	Without Calibration	After Calibration
Satellite (known DCB)	1-5	< 0.5 TECU
Antenna	14-30	< 2 TECU
GNSS Receiver	6-10	< 1 TECU

The ionospheric fluctuations during calibration will impact the final accuracy of the TEC calibration. Moreover, this depends on the following factors:

- Region (Equatorial vs. high latitude),
- Calibration Duration (Start and End Time),
- Local time of the day (night),
- Season (summer/winter), and
- Solar activity (Sun spot cycle).

Hence, it is strongly recommended to perform the TEC calibration when ionospheric activity is at its minimum (i.e. during early hours).

4.6 Calibration Frequency

As with any TEC calibration procedure, the accuracy of calibration generally degrades due to longer ionospheric changes caused by seasonal changes and from solar activity. Hence, the GPStation6 TEC calibration should be performed periodically to account for these longer changes.

A simpler approach is to perform an auto calibration twice a year and apply the new calibration offsets.

Alternatively, the auto calibration can be performed within GPStation6 without interrupting the receiver operation (TEC estimation). With this approach, the auto calibration can be done every few months (2-4 times within a year) and can be analyzed (externally stored in a file for analysis). Note that the changes in TEC calibration offsets will likely include the seasonal/solar activity related TEC variations that should be accounted for. After accounting for the seasonal variations, if the calibration TEC offsets differ by few TECUs, then the new calibration offsets can be applied. Finally, the history of calibration offsets can be potentially used for analyzing longer term systematic effects.

5 References

5.1 NovAtel Documents

Table 5-1 NovAtel Documents

Document #	Document Title
OM-20000132	GNSS Ionospheric Scintillation and TEC Monitor (GISTM) Receiver – User Manual Ref: http://www.novatel.com/assets/Documents/Manuals/om-20000132.pdf
OM-20000129	OEM6 Family Firmware Reference Manual Ref: http://www.novatel.com/assets/Documents/Manuals/om-20000129.pdf

5.2 Other Documents

Table 5-2 Other Documents

Document #	Document Title
[TEC1]	Weather the Storm – GNSS and the Solar Maximum Next Generation GNSS Ionospheric Scintillation and TEC Monitoring Ref: http://www.novatel.com/assets/Documents/Papers/GPStation-6_White_Paper.pdf
[TEC2]	Evolution to Modernized GNSS Ionospheric Scintillation and TEC Monitoring Ref: http://www.novatel.com/assets/Documents/Papers/PID2381119.pdf
[TEC3]	Derivation of TEC and estimation of instrumental biases from GEONET in Japan, 2003. Annales Geophysicase, 21, 2083-2093 Ref: http://www.ann-geophys.net/21/2083/2003/angeo-21-2083-2003.pdf
[TEC4]	http://aiuws.unibe.ch/ionosphere/
[TEC5]	Daily JPL Processing of 1000+ Ground-based GPS Receivers to Estimate Interfrequency Biases and Other Practical Applications Ref:http://igscb.jpl.nasa.gov/igscb/resource/pubs/06_darmstadt/IGS%20Presentations%20PDF/12_1_Komjathy.pdf
[TEC6]	The GPS Segment of the AFRL-SCINDA Global Network and the Challenges of Real-Time TEC Estimation in the Equatorial Ionosphere, ION NTM 2006, 18-20 January 2006, Monterey CA, 1036-1047
[TEC7]	Proia A., Cibiel G., Yaigre L. (2009). Time Stability and Electrical Delay Comparison of Dual-Frequency GPS Receivers, 41st Annual Precise Time and Time Interval (PTTI) Meeting, pp. 293-302.