Improved IONOLAB-TEC Space Weather Service

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OUTLINE

- INTRODUCTION
- GPS-TEC
- GIM-TEC
- IONOLAB-TEC
- RESULTS
- CONCLUSION

INTRODUCTION (1)

- Ionosphere is a highly varying, anisotropic and inhomogeneous magnetoplasma which is very challenging to model and predict.
- The fundamental defining parameter of ionosphere is electron density.
- Electron density can not be measured directly.
- Indirect methods include mathematical, modelling and measurement uncertainties and errors.

INTRODUCTION (2)

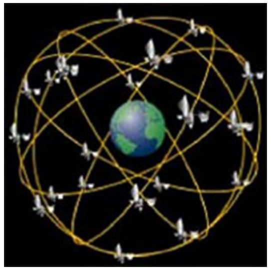
- **Total Electron Content (TEC)** is a derived parameter from electron density and it is defined as the line integral of electron density on a ray path.

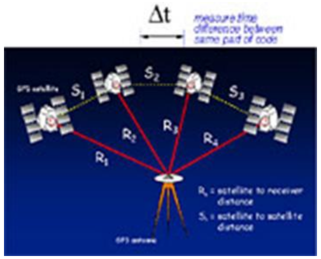
$$\mathrm{TEC} = \int_L N_e \, dl$$

- TEC corresponds to the total number of electrons in a cylindrical tube with 1 m^2 cross-section.
- Unit of TEC is TECU where 1 TECU = 10^{16} el/m^2.
- TEC contains the projection of ionospheric electron distribution and it can be used to model, reconstruct and predict ionospheric variability.
- TEC can be **estimated** (or "**measured**") using ionosondes, incoherent backscatter radars, Faraday Rotation in Beacon Satellite signals, altimeter satellite systems, and Global Navigation Satellite Systems (GNSS).
- Except the use of GNSS signals, measurements are very expensive and extremely sparse in time and space.
- The wide spread use of **Global Positioning System (GPS)** dual-frequency receivers provide a cost-effective solution to estimation of TEC.

GPS-TEC (1)

- GPS is a satellite based navigation system designed and operated by U.S. Department of Defense.
- GPS provides continuous positioning and timing information with an extensive coverage on Earth.
- Space segment is composed of 24-32 satellites in Medium Earth Orbit (MEO) of 20,200 km with a period of 12 hours.
- Two simultaneous L-band signals are transmitted at
- f1=1,575.42 MHz (L1 carrier)
- f2=1,227.60 MHz (L2 carrier)





- Signals are coded with Code Division Multiple Access (CDMA) system for each satellite;
- Coarse acquisition (C/A) Gold code modulated on L1 carrier (Civilian Use)
- Precision (P) code modulated on L1 and L2 carriers (US Military Use)
- U.S. and allied military users of the secure GPS Precise Positioning Service
- Civil, commercial and scientific users of Standard Positioning Service
- With tens of millions of users, GPS became an ultimate
  - positioning tool for commerce, science, mapping, tracking and surveillance
  - timing tool in various applications from banking to power switching

GPS-TEC (2)

- GPS reference station provides a file output: Receiver INdependent EXchange Format (**RINEX**) that contains
  - A Header part: RINEX file and version type, receiver type, antenna type, observer/agency, receiver type, approximate position, types of observations and number of satellites
  - A Data part: epoch (year/day/month/hour/minute/second), number of satellites observed in the epoch, observation types and computed values in each epoch (such as P1/P2/L1/L2)
- Typical RINEX file records information every 30 s and RINEX files are produced daily.
- Reference station data in the form of pseudorange and phase delay are used in TEC calculation.
- RINEX format has various versions and most GPS receivers use version 2.11.
- Recently, RINEX 3.0 series is introduced with different pseudorange and phase delay designations.

GPS-TEC (3)

- Pseudorange and Phase Delay are computed in the digital (software) section of the receiver in a microprocessor.
- General operations on the received signals are well documented and easily be reconstructed.
- TEC estimation is related to the software part that is contained in the microprocessor.
- Civilian GPS companies do not provide specific (exact) information on how they produce pseudorange and phase delay information in the microprocessor.
- Different RINEX versions have different signal designations for pseudorange and phase delay.
- RINEX 3.01:

System	Freq. Band	Frequency	Channel or Code	Observation Codes: Pseudo Range	Carrier Phase	Doppler	Signal Strength
GPS	L1	1575.42	C/A	C1C	L1C	D1C	S1C
			L1C (M)	C1S	L1S	D1S	S1S
			L1C (L)	C1L	L1L	D1L	S1L
			L1C (M+L)	C1X	L1X	D1X	S1X
			P	C1P	L1P	D1P	S1P
			Z-tracking and similar (AS on)	C1W	L1W	D1W	S1W
			Y	C1Y	L1Y	D1Y	S1Y
			M	C1M	L1M	D1M	S1M
			codeless	--	L1N	D1N	S1N
	L2	1227.60	C/A	C2C	L2C	D2C	S2C
			L1(C/A)+(P2-P1) (semi-codeless)	C2D	L2D	D2D	S2D
			L2C (M)	C2S	L2S	D2S	S2S
			L2C (L)	C2L	L2L	D2L	S2L
			L2C (M+L)[1]	C2X	L2X	D2X	S2X
			P	C2P	L2P	D2P	S2P
			Z-tracking and similar (AS on)	C2W	L2W	D2W	S2W
			Y	C2Y	L2Y	D2Y	S2Y
			M	C2M	L2M	D2M	S2M
			codeless	--	L2N	D2N	S2N

- RINEX 2.11:

```
+----------------------------------------------------------------------------+
| System   Freq.Band   Frequency          RINEX 2-character Code              |
|                                Ps.Range  Carr.Phase  Doppler  Sign.Strength |
+----------------------------------------------------------------------------+
| GPS      L1          1575.42    C1,P1       L1         D1          S1      |
|          L2          1227.60    C2,P2       L2         D2          S2      |
```

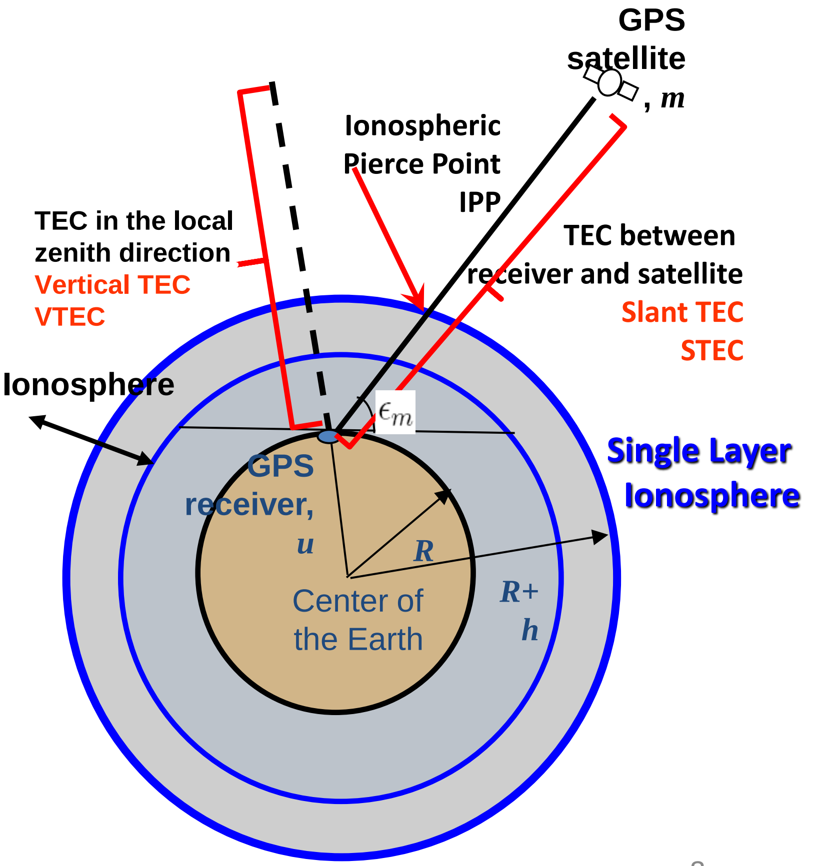
GPS-TEC (4)

- Ionospheric delay is estimated from geometry-free combination of pseudorange and phase delay.
- Slant TEC (STEC) on the ray path between satellite m and receiver u
- Single Layer Ionosphere Model (SLIM) assumes that the most effective ionization, therefore, the most number of electrons are concentrated at the maximum ionization height of F2 layer, hmF2.
- Vertical TEC (VTEC) is a function of this height, h, and local elevation angle of the satellite.
- Azimuthal variation of the ionosphere is totally ignored.

$$VTEC_u^m(n) = STEC_u^m(n)/M(\epsilon_m(n))$$

$$M(\epsilon_m(n)) = \left[1 - \left(\frac{R\cos\epsilon_m(n)}{R+h}\right)^2\right]^{-1/2}$$

$$\begin{aligned} d_{ion,u}^m &= -\Phi_{ion,u}^m \frac{c}{f} \\ &\approx A\frac{STEC_u^m}{f^2} \end{aligned}$$

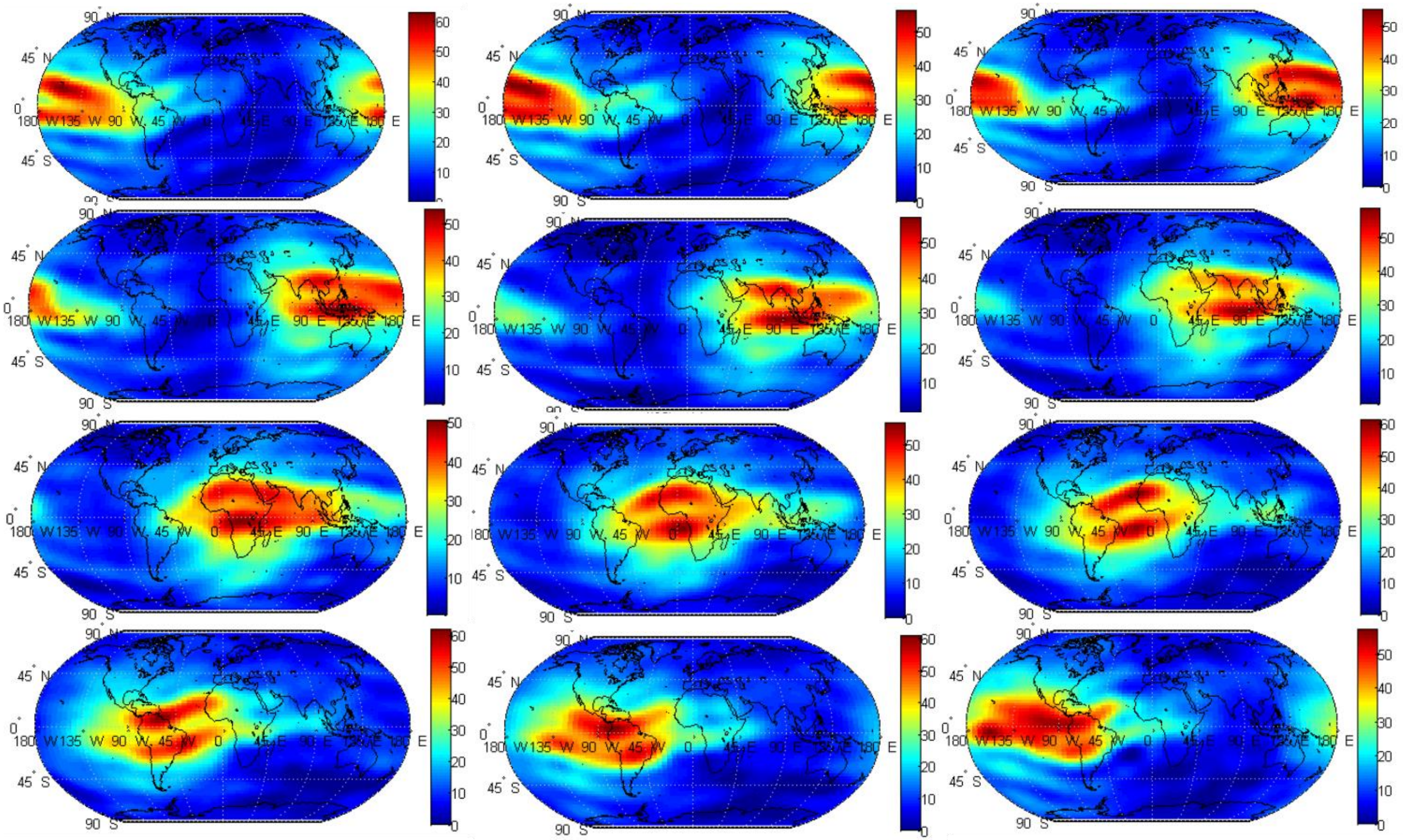


GIM-TEC (1)

- **Global Ionospheric Maps (GIM) of TEC (GIM-TEC) from International GPS Service for Geodynamics (IGS) centers** in IONosphere map EXchange **(IONEX)** format.
- **ftp://cddisa.gsfc.nasa.gov/gps/products/ionex/**
- Spatial Resolution : 5^0 in longitude and 2.5^0 in latitude
- Temporal Resolution : 2 hours/1 hour
- CODE - Center for Orbit Determination in Europe, University of Berne, Switzerland (http://www.aiub.unibe.ch/ionosphere.html).
- ESA/ESOC - European Space Operations Center of European Space Agency, Darmstadt, Germany (http://nng.esoc.esa.de/gps/ionmon.html).
- JPL-GNISD - Jet Propulsion Laboratory,Pasadena, California, USA (http://iono.jpl.nasa.gov).
- gAGE/UPC - Polytechnical University of Catalonia, Barcelona, Spain (http://maite152.upc.es/~ionex/gAGE_dip/gAGE_dip.html).
- **IGS-gAGE**
- Various products for final and predicted GIM-TEC.

GIM-TEC (2)

GIM-TEC from CODE, 27 MARCH 2010
0000 UT – 2200 UT, 2 h resolution



GIM-TEC (3)

Data & Products

ABOUT IGS | ORGANIZATION | FAQs | FTP ARCHIVES | WEBSITE INDEX

▶ USING DATA & PRODUCTS ▶ DATA HOLDINGS ▶ PRODUCTS

IGS Products

What happened in the latest IGS Ultrarapid analysis? Click here!

The IGS collects, archives, and distributes GPS and GLONASS observation data sets of sufficient accuracy to meet the objectives of a wide range of scientific and engineering applications and studies. These data sets are analyzed and combined to form the IGS products shown in the table below.

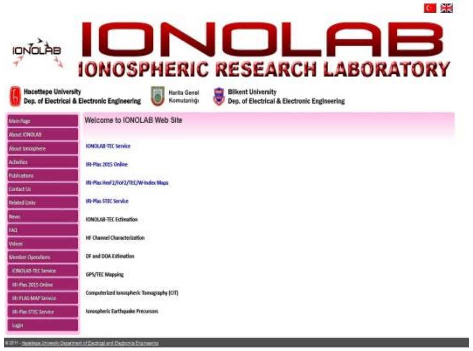
IGS products support scientific activities such as improving and extending the International Terrestrial Reference Frame (ITRF) maintained by the International Earth Rotation and Reference Systems Service (IERS), monitoring deformations of the solid Earth and variations in the liquid Earth (sea level, ice sheets, etc.) and in Earth rotation, determining orbits of scientific satellites, and monitoring the troposphere and ionosphere.

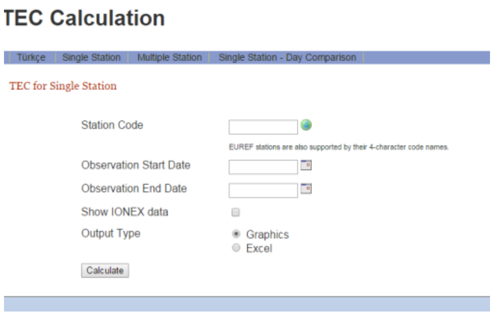
IGS Product Table [GPS Broadcast values included for comparison] -- updated for 2009!

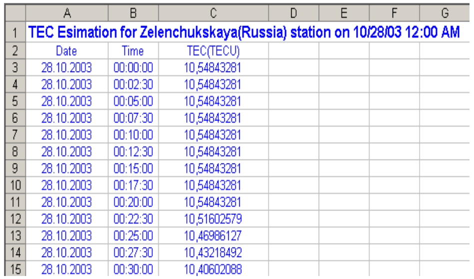
		Accuracy	Latency	Updates	Sample Interval	Archive locations
GPS Satellite Ephemerides/ Satellite & Station Clocks						
Broadcast	orbits	~100 cm	real time	--	daily	CDDIS(US-MD) SOPAC(US-CA) IGN(FR)
	Sat. clocks	~5 ns RMS ~2.5 ns SDev				
Ultra-Rapid (predicted half)	orbits	~5 cm	real time	at 03, 09, 15, 21 UTC	15 min	CDDIS(US-MD) IGS CB(US-CA) SOPAC(US-CA) IGN(FR) KASI (KOREA)
	Sat. clocks	~3 ns RMS ~1.5 ns SDev				
Ultra-Rapid (observed half)	orbits	~3 cm	3 - 9 hours	at 03, 09, 15, 21 UTC	15 min	CDDIS(US-MD) IGS CB(US-CA) SOPAC(US-CA) IGN(FR) KASI (KOREA)
	Sat. clocks	~150 ps RMS ~50 ps SDev				
Rapid	orbits	~2.5 cm	17 - 41 hours	at 17 UTC daily	15 min	CDDIS(US-MD) IGS CB(US-CA) SOPAC(US-CA) IGN(FR) KASI (KOREA)
	Sat. & Stn. clocks	~75 ps RMS ~25 ps SDev			5 min	
Final	orbits	~2.5 cm	12 - 18 days	every Thursday	15 min	CDDIS(US-MD) IGS CB(US-CA) SOPAC(US-CA) IGN(FR) KASI (KOREA)
	Sat. & Stn. clocks	~75 ps RMS ~20 ps SDev			Sat.: 30s Stn.: 5 min	
Atmospheric Parameters						
Final tropospheric zenith path delay		4 mm	< 4 weeks	weekly	2 hours	CDDIS(US-MD) IGN(FR) KASI(KOREA) SOPAC(US-CA)
Ultra-Rapid tropospheric zenith path delay		6 mm	2-3 hours	every 3 hours	1 hour	CDDIS(US-MD) KASI(KOREA)
Final ionospheric TEC grid		2-8 TECU	~11 days	weekly	2 hours; 5 deg (lon) x 2.5 deg (lat)	CDDIS(US-MD) IGN(FR) KASI(KOREA)
Rapid ionospheric TEC grid		2-9 TECU	<24 hours	daily	2 hours; 5 deg (lon) x 2.5 deg (lat)	CDDIS(US-MD) IGN(FR) KASI(KOREA)

IONOLAB-TEC (1)

- **IONOLAB-TEC** is the *state-of-the-art* signal processing technique for GPS-TEC estimation for a single station.
- IONOLAB-TEC provides accurate, reliable and robust GPS-TEC estimation for **ANY** high latitude, midlatitude, or equatorial GPS station for both quiet and disturbed days with the same reliability and accuracy.
- IONOLAB-TEC combines data from all the GPS satellites that are above 10^0 elevation angle (horizon limit) of the GPS station with a temporal resolution of 30 s. The method calculates VTEC per satellite and combines them using a weighting function based on satellite positions which reduces the contamination caused by multipath effects.
- The receiver DCB is estimated using **IONOLAB-BIAS** method.
- An online user-friendly service at www.ionolab.org for any IGS, EUREF or private GPS networks.
- Unique service with both graphical or text output.







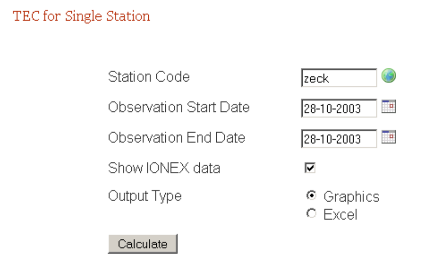
	A	B	C	D	E	F	G
1	TEC Esimation for Zelenchukskaya(Russia) station on 10/28/03 12:00 AM						
2	Date	Time	TEC(TECU)				
3	28.10.2003	00:00:00	10,54843281				
4	28.10.2003	00:02:30	10,54843281				
5	28.10.2003	00:05:00	10,54843281				
6	28.10.2003	00:07:30	10,54843281				
7	28.10.2003	00:10:00	10,54843281				
8	28.10.2003	00:12:30	10,54843281				
9	28.10.2003	00:15:00	10,54843281				
10	28.10.2003	00:17:30	10,54843281				
11	28.10.2003	00:20:00	10,54843281				
12	28.10.2003	00:22:30	10,51602579				
13	28.10.2003	00:25:00	10,46986127				
14	28.10.2003	00:27:30	10,43218492				
15	28.10.2003	00:30:00	10,40602088				

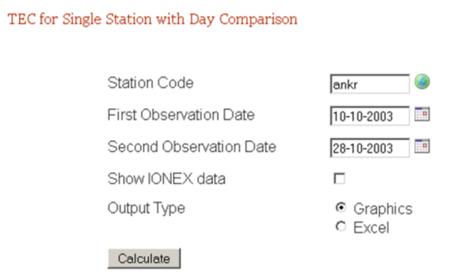
IONOLAB-TEC (2)

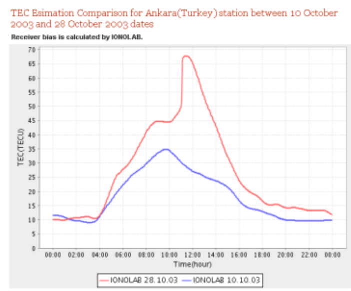
IONOLAB-TEC can be computed for

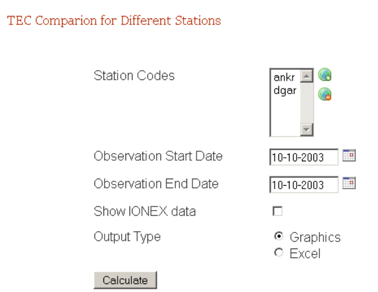
- ✓ any single IGS or EUREF station(s) and certain private networks,
- ✓ for one day or a number of days with 2.5 min time resolution,

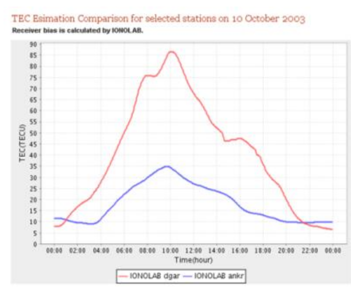
computation of IONOLAB-TEC includes IONOLAB-BIAS for all stations and a comparison with IGS analysis center results is also presented on user demand.



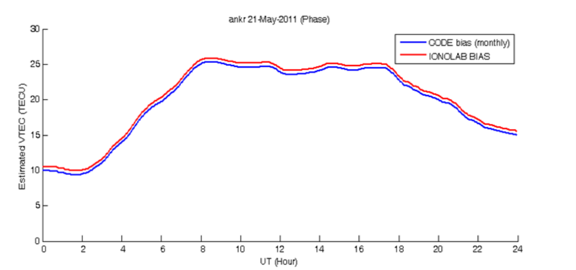


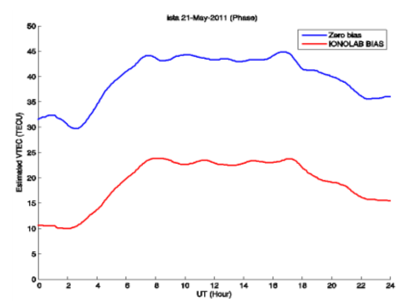


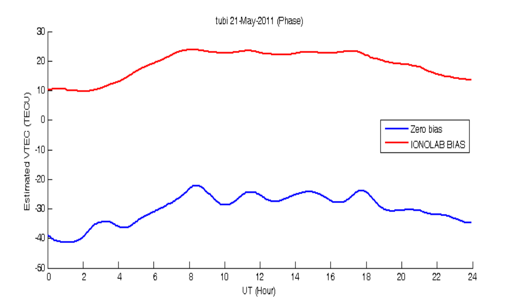




Effect of IONOLAB-BIAS

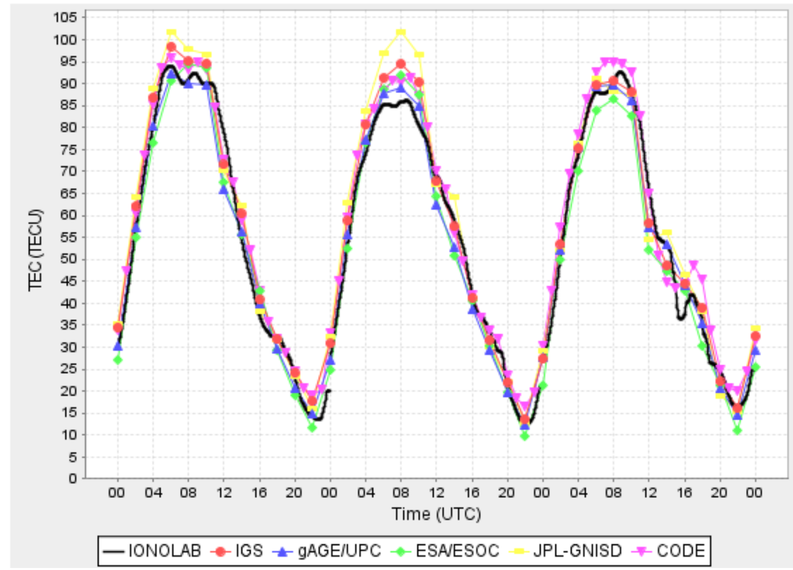




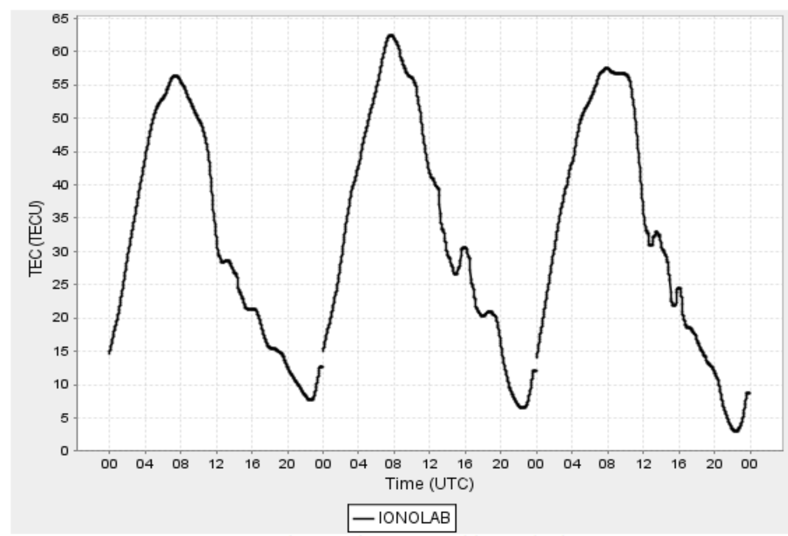


IONOLAB-TEC (3)

- cusv station in Bangkok, Thailand
- 29-31 October 2014

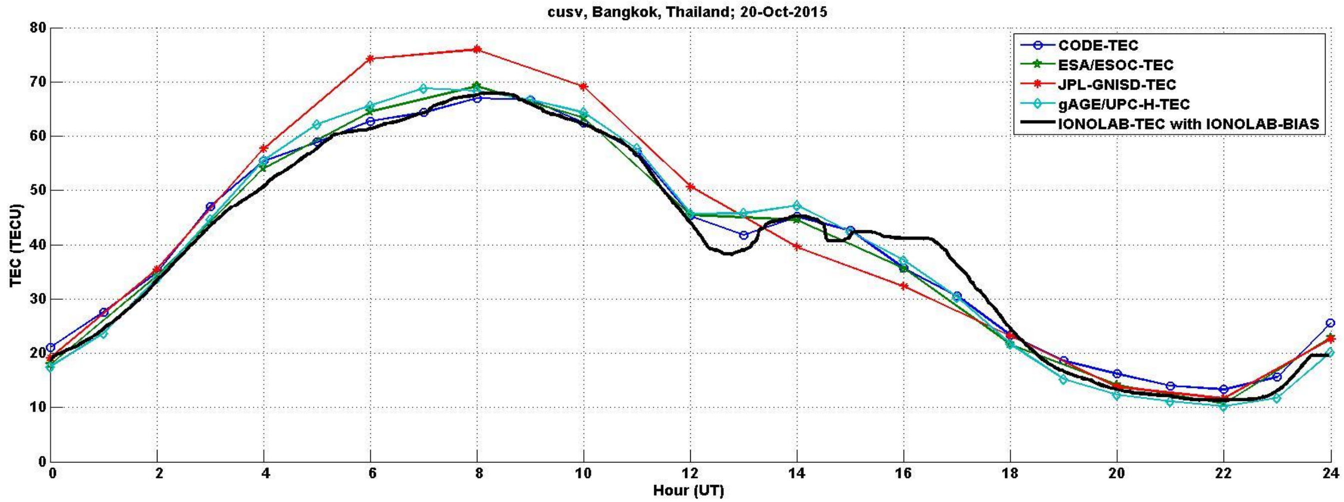


- 29-31 October 2015 (computed on 1 November, 2015)

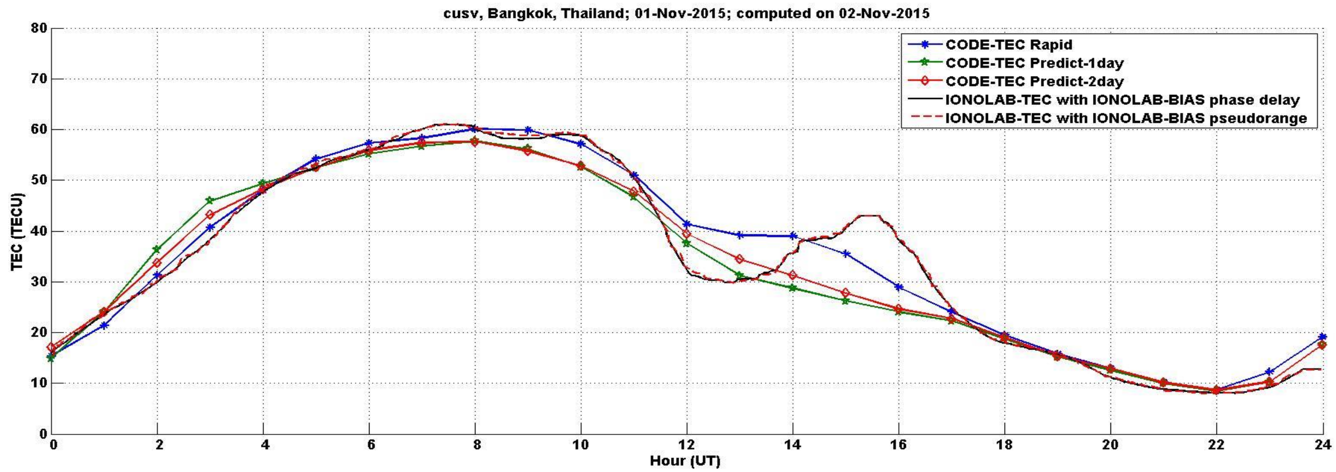


IONOLAB-TEC (4)

- cusv, Bangkok, Thailand
- 20 October, 2015



- 01 November, 2015



- Both computed on 02 November, 2015

IONOLAB-TEC (5)

- Improved IONOLAB-TEC can be estimated automatically
  - from both RINEX 2.11 and (for the first time in literature as an automatic online service) RINEX 3.01 and 3.02 files;
  - using any time resolution from starting from 1 s;
  - using both 24-hour and 15 min packed RINEX files (near real-time);
  - using final and predicted IONEX products.
- IONOLAB-BIAS will be automatically computed with available IONEX map.
- **IONOLAB-TEC.exe** will be available as an executable file for one station and one day by the end of November 2015!!
- The output will be provided with 30 s time resolution in a text file.

RINEX 2.11 vs. RINEX 3.0x

System	Freq. Band	Frequency	Channel or Code	Observation Codes: Pseudo Range	Carrier Phase	Doppler	Signal Strength
GPS	L1	1575.42	C/A	C1C	L1C	D1C	S1C
			L1C (M)	C1S	L1S	D1S	S1S
			L1C (L)	C1L	L1L	D1L	S1L
			L1C (M+L)	C1X	L1X	D1X	S1X
			P	C1P	L1P	D1P	S1P
			Z-tracking and similar (AS on)	C1W	L1W	D1W	S1W
			Y	C1Y	L1Y	D1Y	S1Y
			M	C1M	L1M	D1M	S1M
			codeless	--	L1N	D1N	S1N
	L2	1227.60	C/A	C2C	L2C	D2C	S2C
			L1(C/A)+(P2-P1) (semi-codeless)	C2D	L2D	D2D	S2D
			L2C (M)	C2S	L2S	D2S	S2S
			L2C (L)	C2L	L2L	D2L	S2L
			L2C (M+L)[1]	C2X	L2X	D2X	S2X
			P	C2P	L2P	D2P	S2P
			Z-tracking and similar (AS on)	C2W	L2W	D2W	S2W
			Y	C2Y	L2Y	D2Y	S2Y
			M	C2M	L2M	D2M	S2M
			codeless	--	L2N	D2N	S2N

All IGS stations publish in RINEX 2.11 format.

Over 100 IGS stations also publish in RINEX 3.02 format.

For TEC computation using RINEX 3.0x: C1W (or C1C), C2W, L1W (or L1C) and L2W (or L2X)

Satellite DCB: use P1-C1 file values for P1 (or RINEX3: C1W) and C1 (or RINEX3: C1C) along with P1-P2 file values

System	Freq.Band	Frequency	RINEX 2-character Code: Ps.Range	Carr.Phase	Doppler	Sign.Strength
GPS	L1	1575.42	C1,P1	L1	D1	S1
	L2	1227.60	C2,P2	L2	D2	S2
	L5	1176.45	C5	L5	D5	S5

For TEC computation using RINEX 2.11: P1 (or C1), P2, L1 and L2

RESULTS (1)

- Improved IONOLAB-TEC is demonstrated using two GNSS receivers located in Ankara, Turkey between 6 - 11 August 2015
  - 6-7 August 2015: positively disturbed days and 10-11 August 2015: quiet days

- ankr

TOPCON/Javad

TOPCON TPSCR3_GGD with radome CONE

- geoa

ASHTEC/Proflex 800

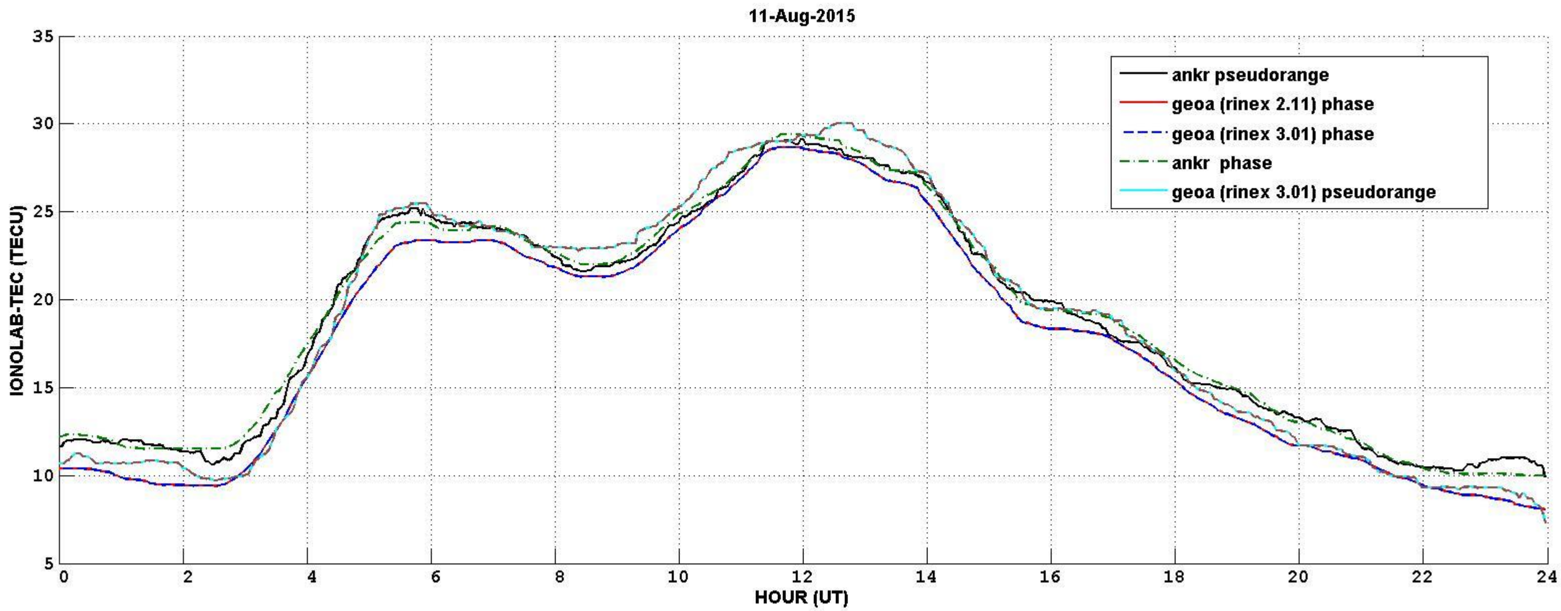
ASHTEC ASH111661

ankr is an IGS/EUREF station operate by General Command of Mapping
geoa station is a property of Geomatics Inc. (http://geomaticsgroup.com/)

	geoa	ankr
Coordinates	39°51'49.74“ N 32°42'5.07“ E	39°53'15.00“ N 32°45'30.96“ E
Recording frequency	15 s	15 s
Recording period	15 min and 24 h	15 min and 24 h
Recording format	RINEX and raw data	RINEX only
RINEX format	2.11 and 3.01 (all formats from raw data)	2.11 only

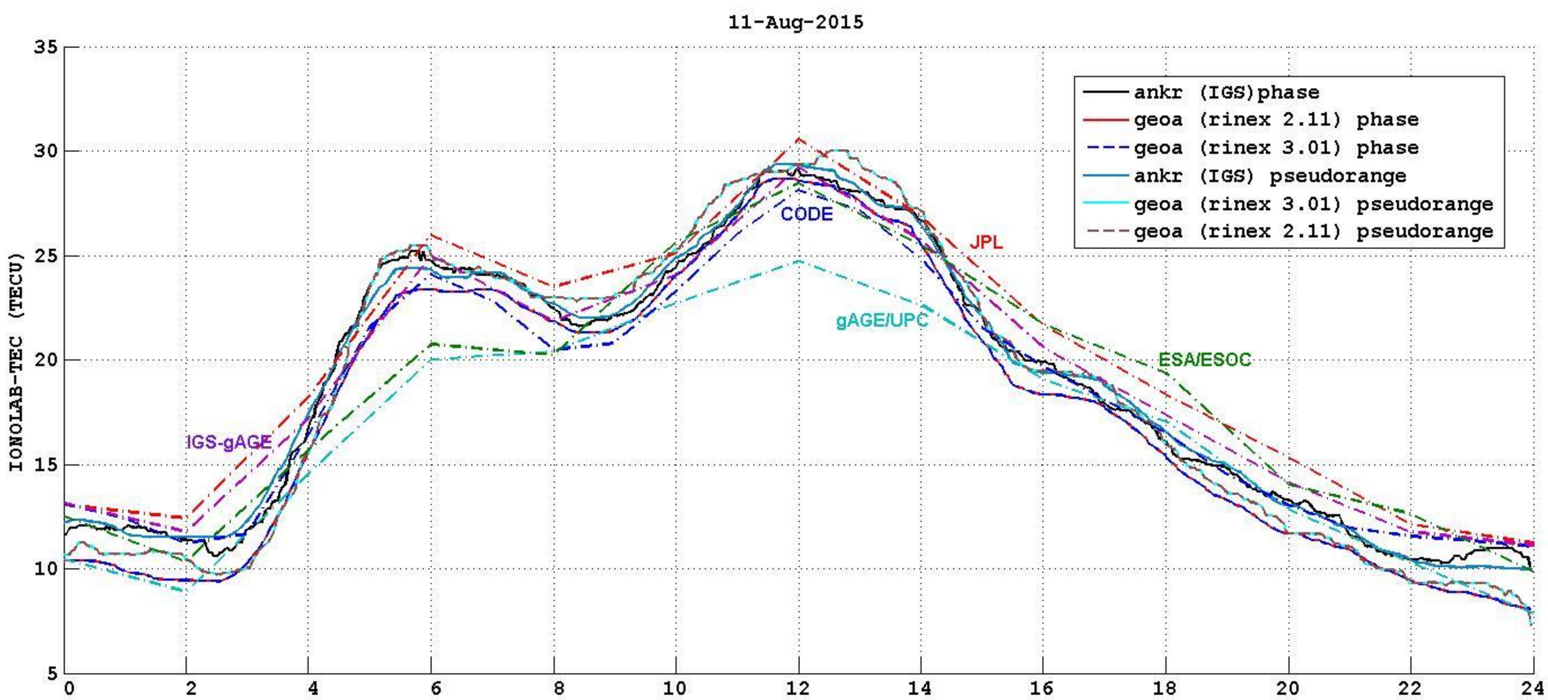
RESULTS (2)

- **August 11, 2015**, IONOLAB-TEC estimates from **ankr** and **geoa** are computed from pseudorange and phase delay using both RINEX 2.11 and 3.01 versions.



RESULTS (3)

- **August 11, 2015**, IONOLAB-TEC estimates from **ankr** and **geoa** are computed from pseudorange and phase delay using both RINEX 2.11 and 3.01 versions and **compared with GIM-TEC interpolated values**.

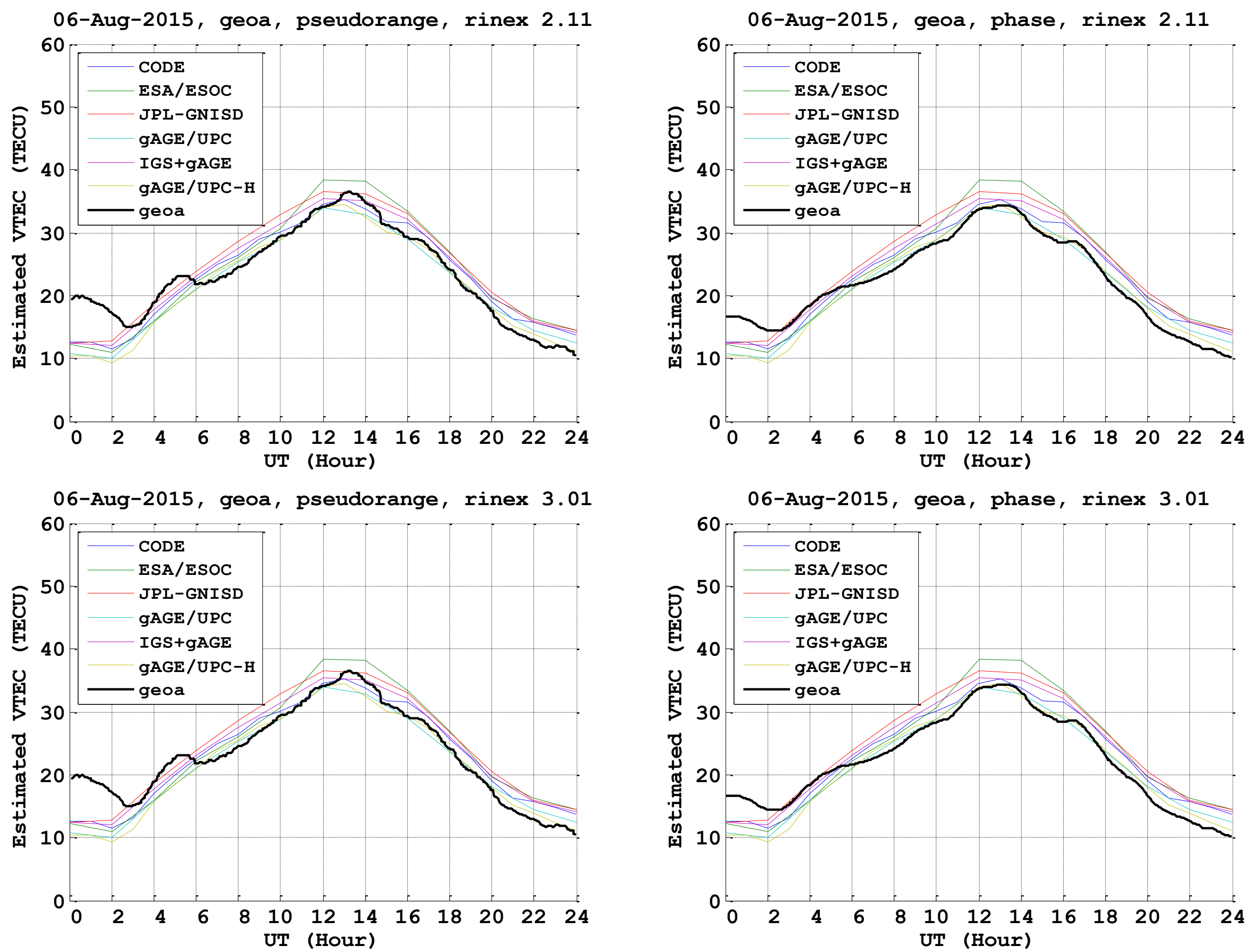


RESULTS (4)

6 August 2015, geoa receiver, IONOLAB-TEC Comparison

Rinex 2.11

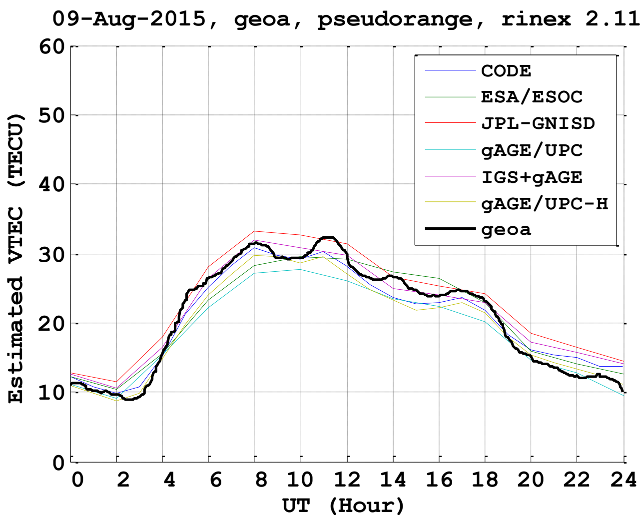
Rinex 3.01

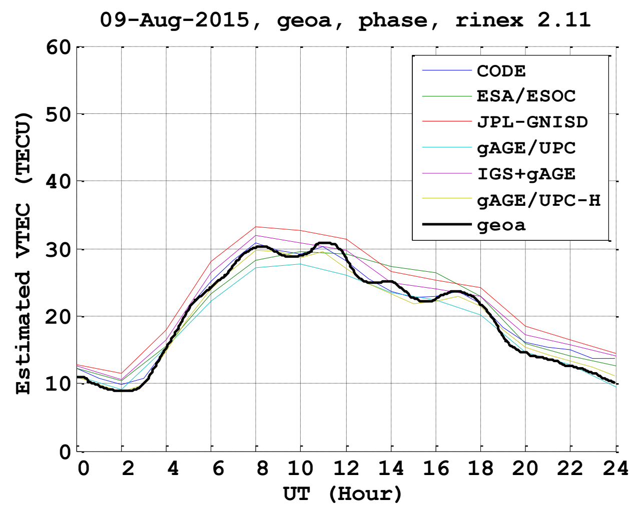


RESULTS (5)

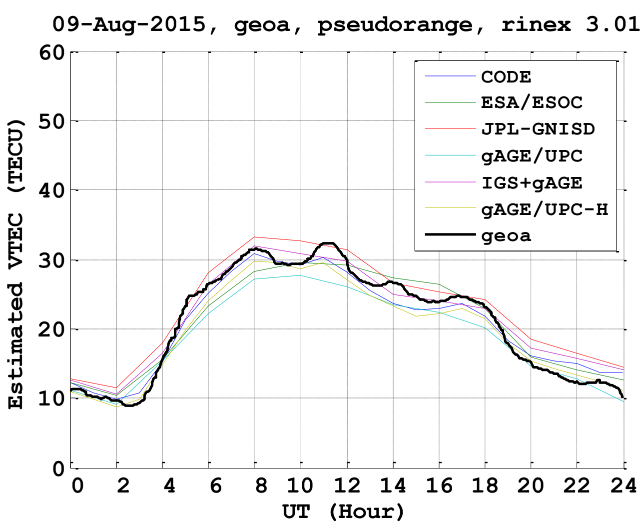
9 August 2015, geoa receiver, IONOLAB-TEC Comparison

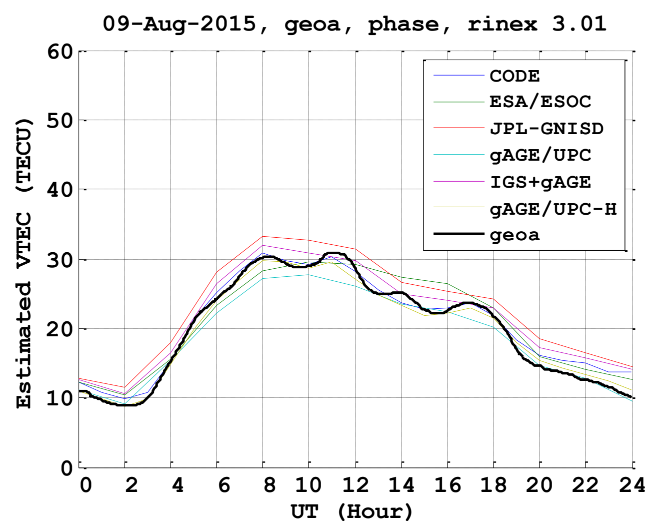
Rinex 2.11





Rinex 3.01





CONCLUSION (1)

- TEC provides an ‘experimental’ and ‘instantaneous’ projection of electron density; thus, it carries information on space weather variability.
- GPS reference stations are cost-effective to install and operate compared to other devices for ionospheric investigation.
- **IONOLAB-TEC** obtained from single GPS station provides **accurate, reliable, automatic and near real-time** TEC estimates with **any sampling interval and any packaging period**.
- Comparison with available IGS IONEX estimates can be provided on demand automatically.
- IONOLAB-TEC is the only service that can compute TEC from both RINEX 2.11 and 3.0x formats.
- **www.ionolab.org**

CONCLUSION (2)

- RINEX 3.0x is a new format for recording GNSS measurements. It offers new signals with different characteristics as compared to RINEX 2.11.

- All IGS receivers still record in RINEX 2.11 format and TEC estimates are calculated from these recordings.
- However, over 100 IGS receivers have already begun to record in RINEX 3.02 also and the number is expected to increase.

- A new tool for estimating TEC values from RINEX 3.01 measurements has been developed in this study.
- It has been shown that TEC estimates from RINEX 3.01 closely follow estimates from RINEX 2.11 and IONEX maps also.
  - During quiet days the deviation is almost within 1 TECU (~10 %) and during disturbed days the deviation is less than 3-4 TECUs (~20 %).

- Sezen, U., Arikan, F., Arikan, O., Ugurlu, O., & Sadeghimorad, A. (2013). Online, automatic, near-real time estimation of GPS-TEC: IONOLAB-TEC.*Space Weather*, *11*(5), 297-305.
- http://onlinelibrary.wiley.com/doi/10.1002/swe.20054/full

THANKS

- **Joint TÜBİTAK 112E568 and RFBR 13-02-91370-Cta**
- **Joint TÜBİTAK 114E092 and AS CR 14/001**
- **TÜBİTAK 114E541**

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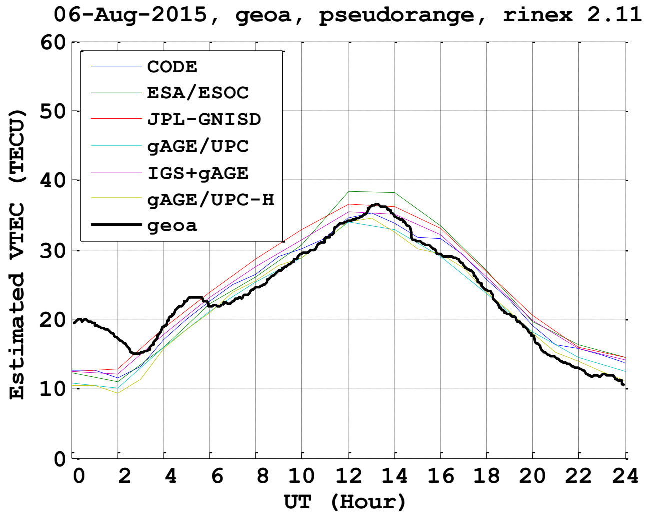
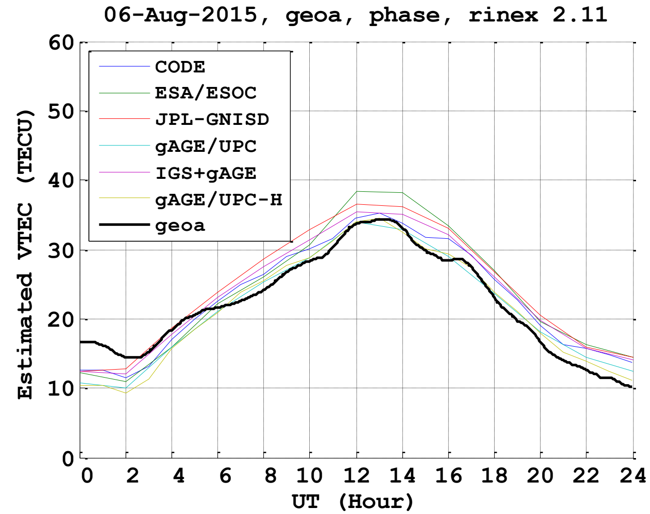
Your Contributions are Welcome!
Limited funding may be available for young scientists and researchers!!

6 August 2015, geoa receiver, Estimated VTEC Comparison

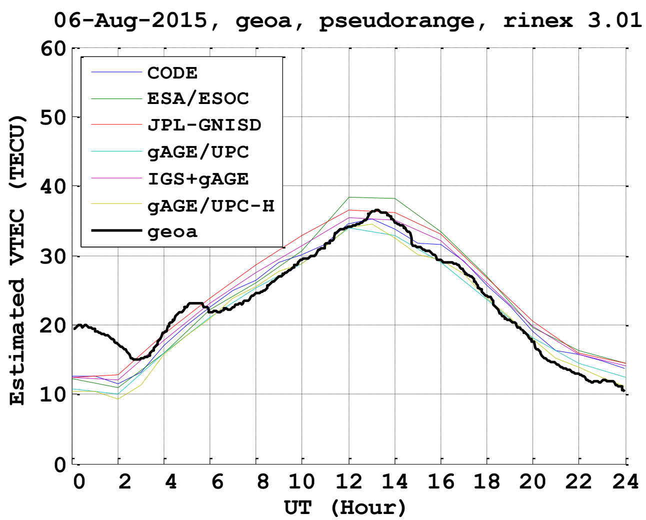
TEC from pseudorange | **TEC from phase**

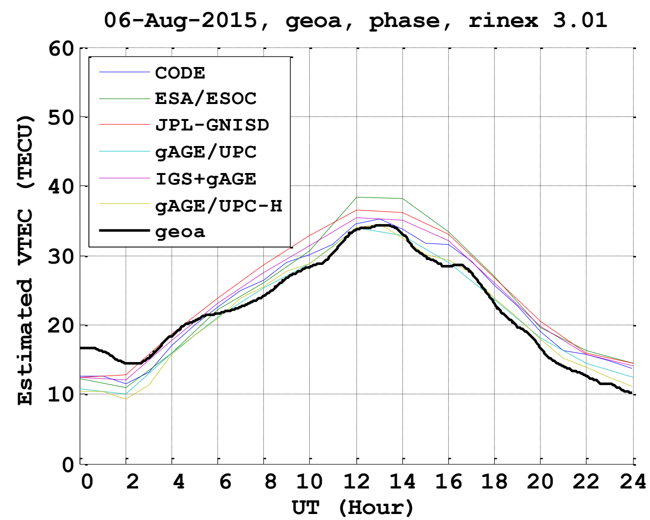
Rinex 2.11





Rinex 3.01

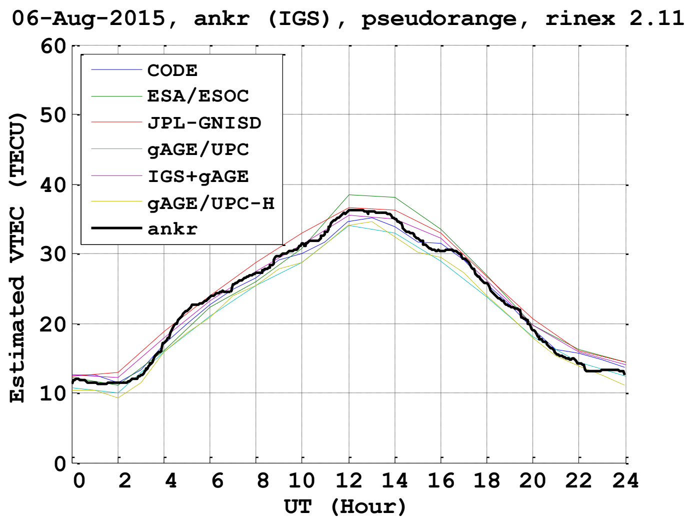


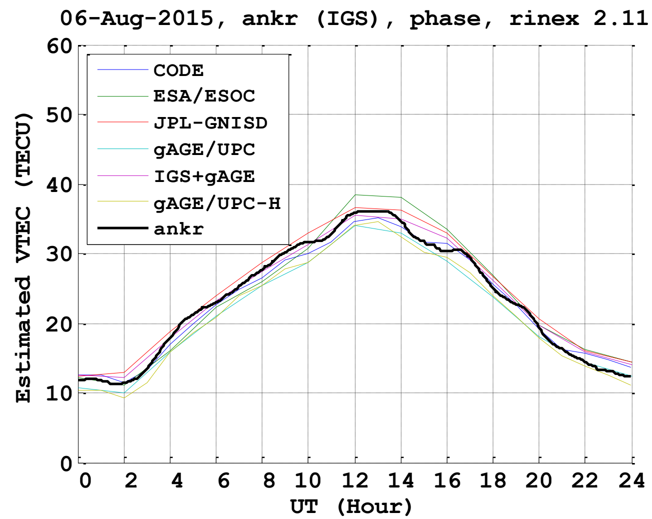


6 August 2015, ankr (IGS) receiver, Estimated VTEC Comparison

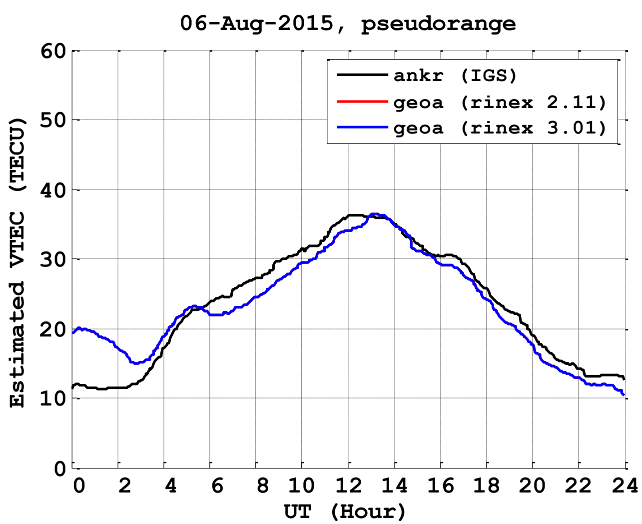
TEC from pseudorange | **TEC from phase**

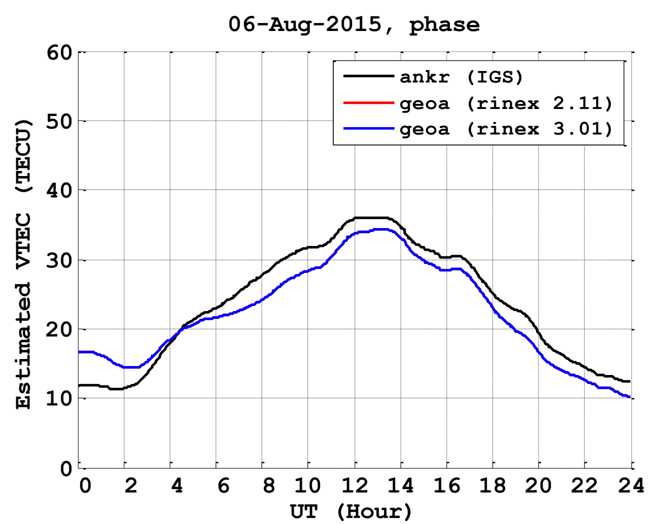
Rinex 2.11





ankr vs. geoa

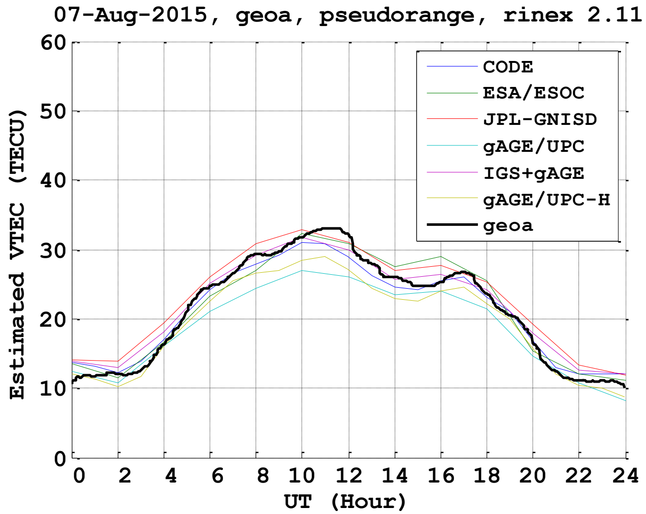


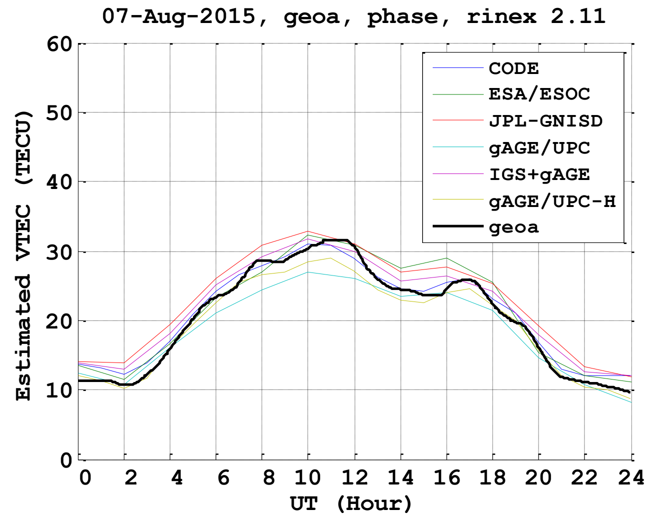


7 August 2015, geoa receiver, Estimated VTEC Comparison

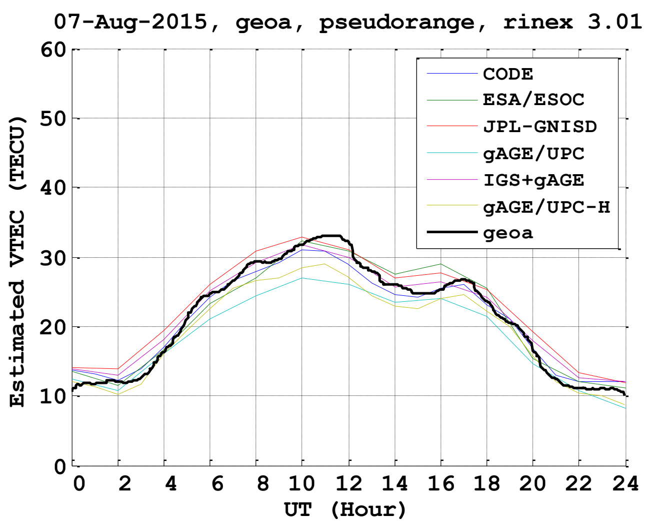
TEC from pseudorange | **TEC from phase**

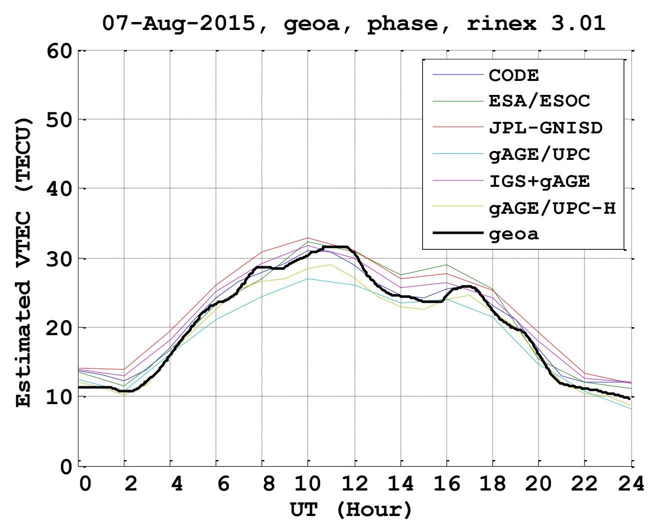
Rinex 2.11



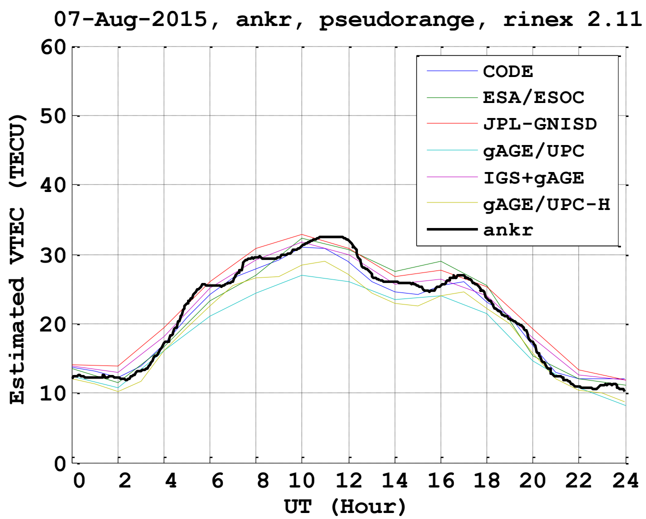
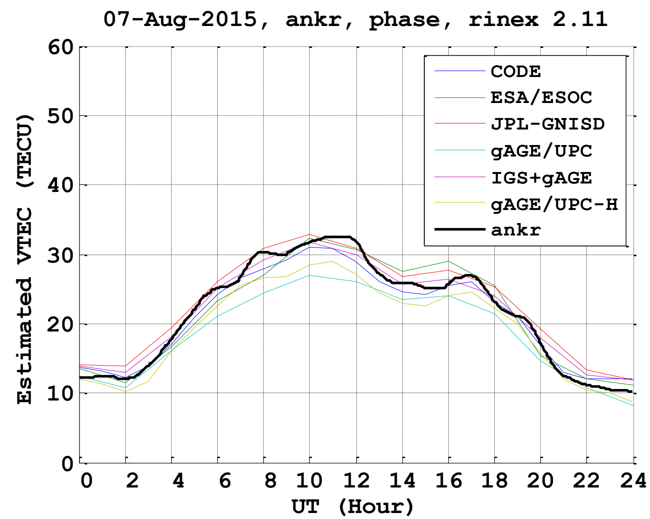
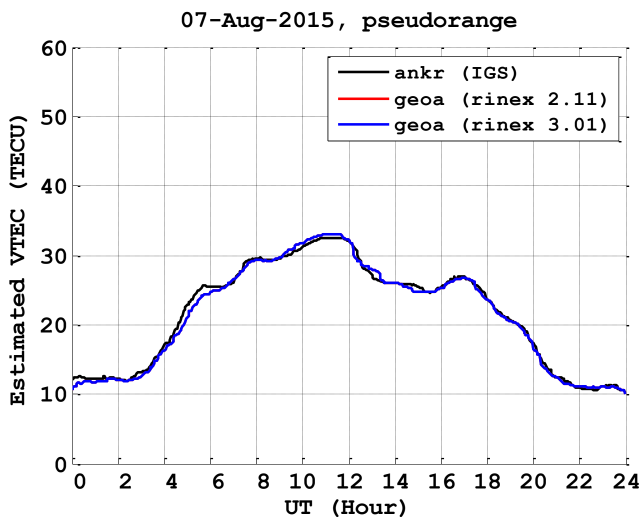
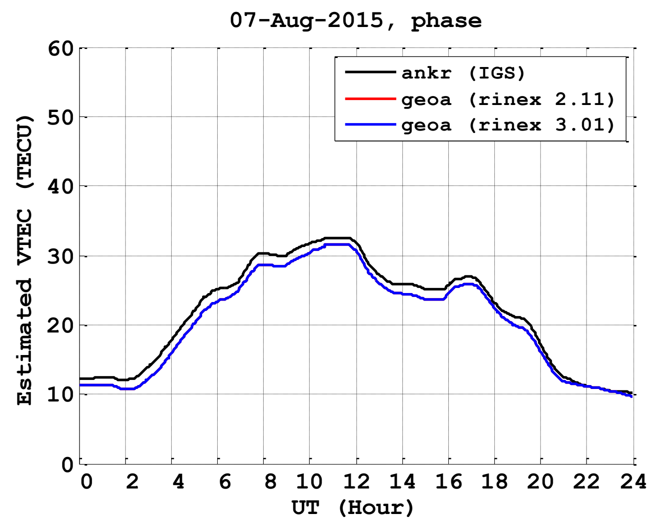


Rinex 3.01





7 August 2015, ankr (IGS) receiver, Estimated VTEC Comparison

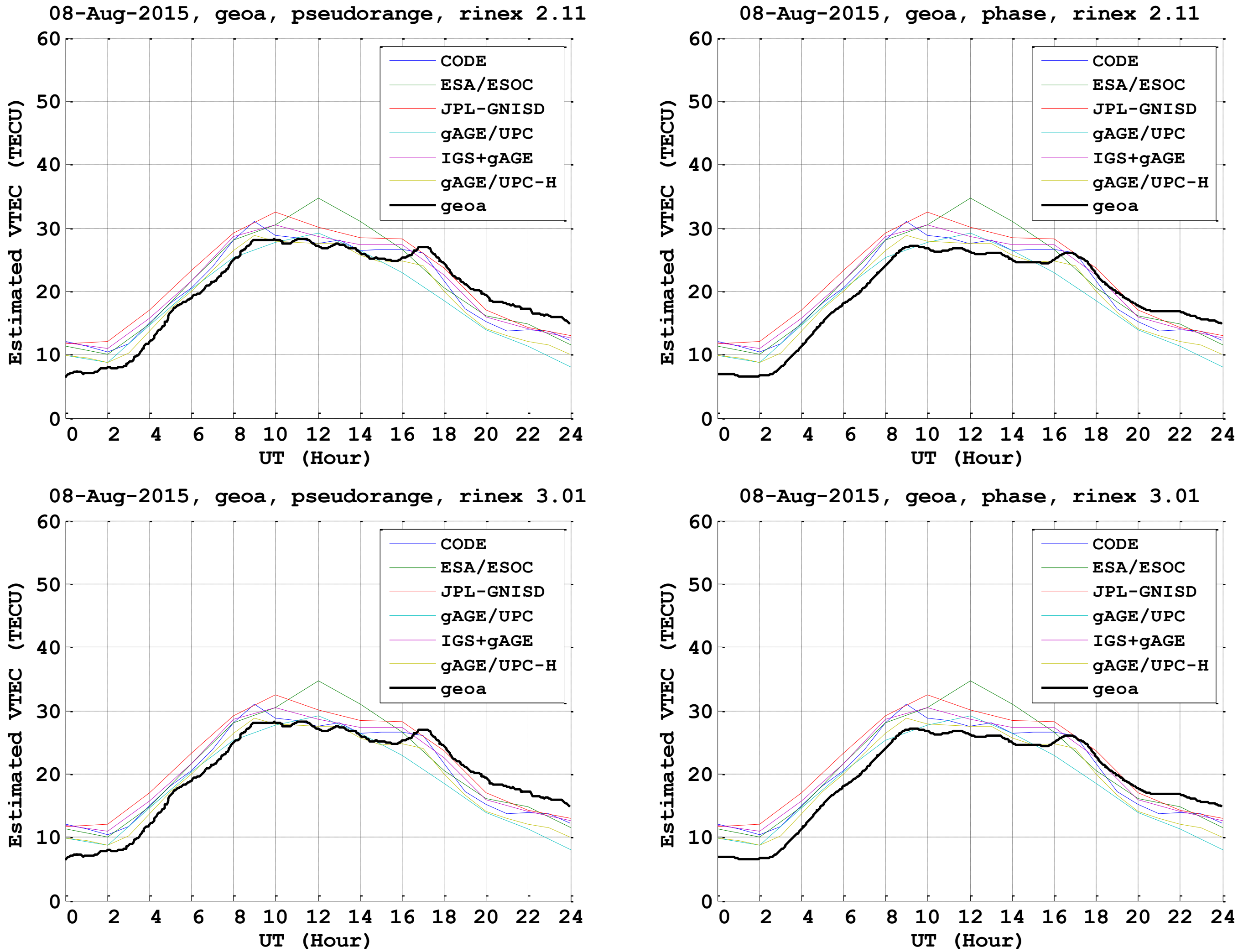
	TEC from pseudorange	TEC from phase
Rinex 2.11		
ankr vs. geoa		

8 August 2015, geoa receiver, Estimated VTEC Comparison

TEC from pseudorange | **TEC from phase**

Rinex 2.11

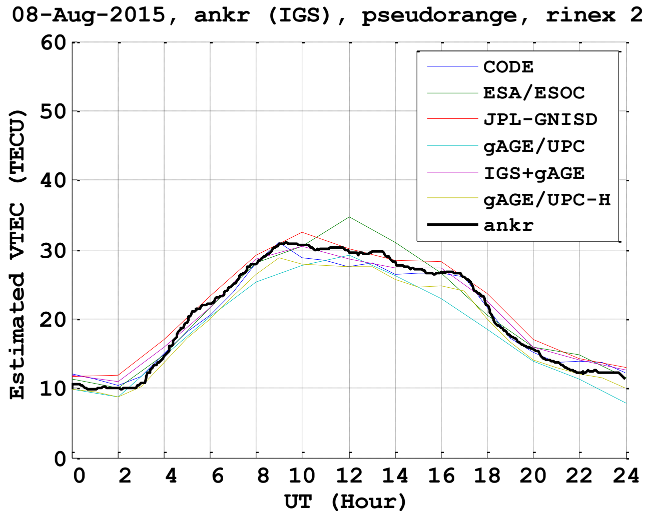
Rinex 3.01

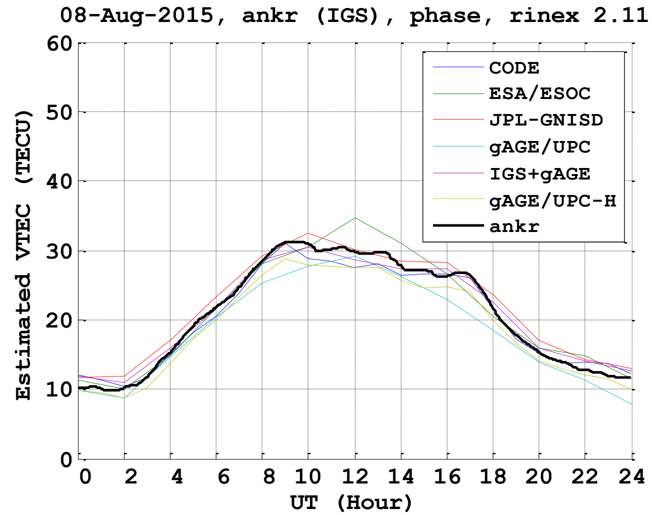


8 August 2015, ankr (IGS) receiver, Estimated VTEC Comparison

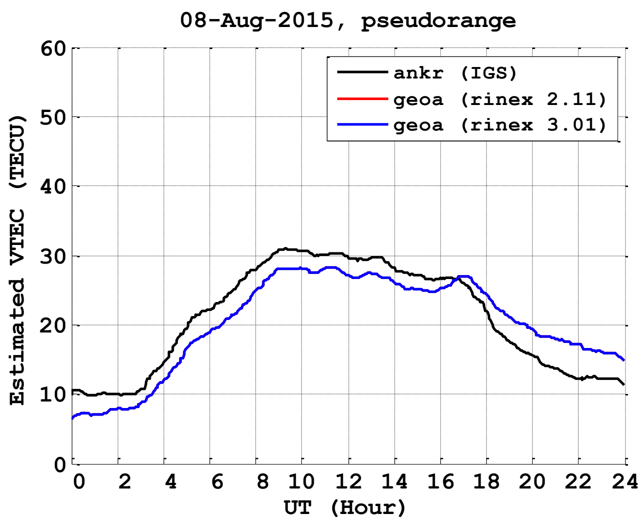
TEC from pseudorange | **TEC from phase**

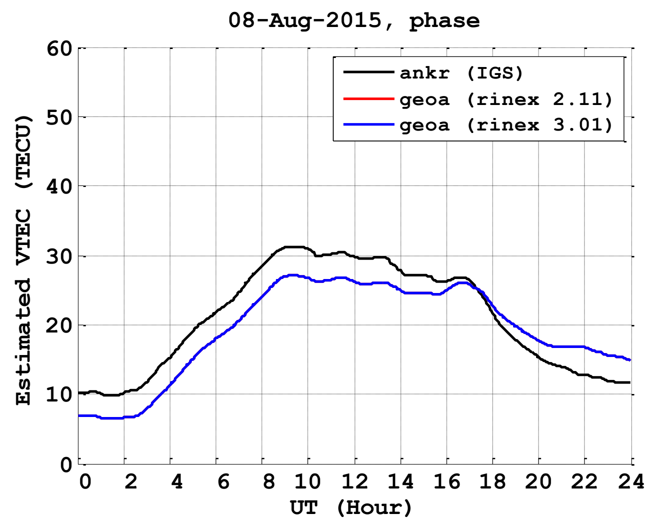
Rinex 2.11





ankr vs. geoa

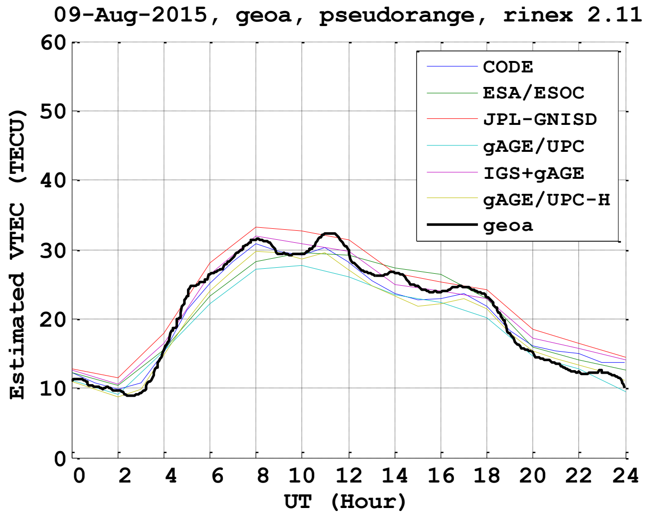


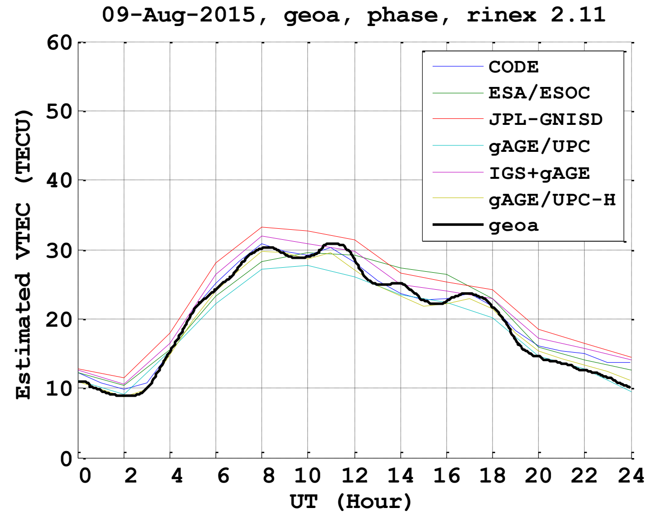


9 August 2015, geoa receiver, Estimated VTEC Comparison

TEC from pseudorange | **TEC from phase**

Rinex 2.11





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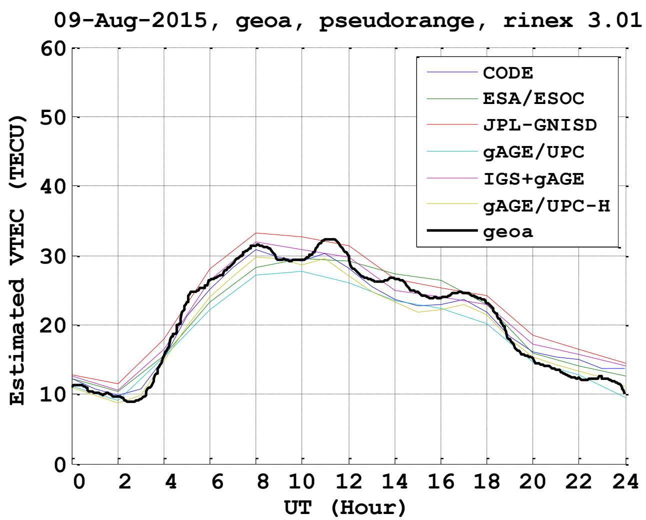
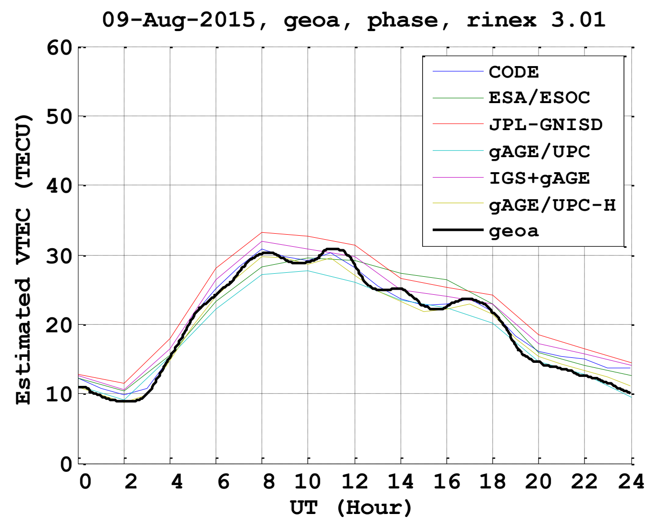
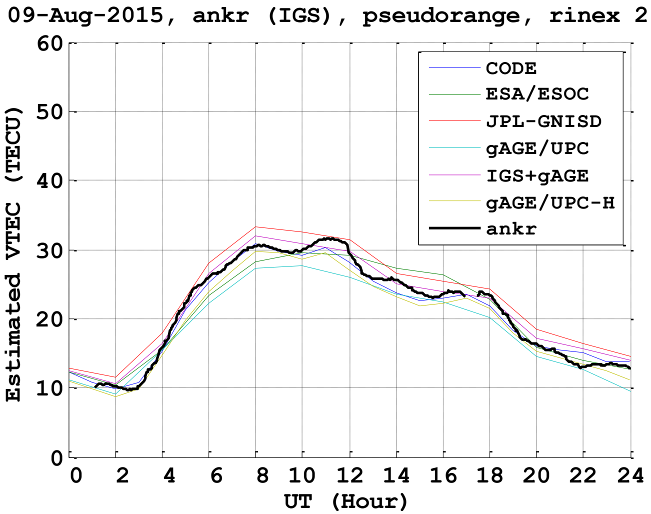


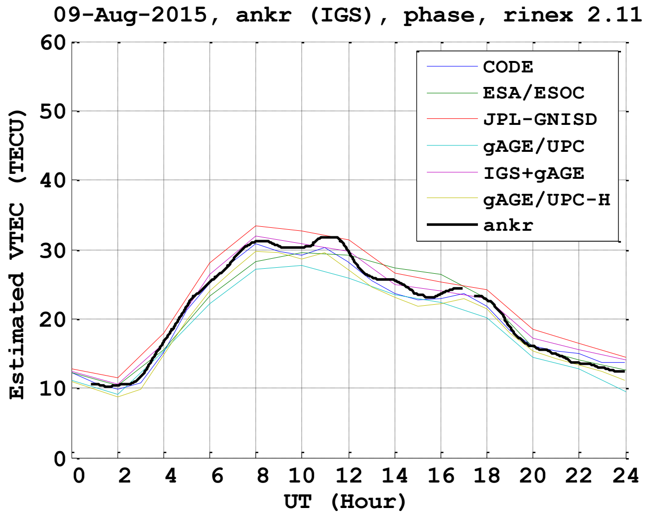


9 August 2015, ankr (IGS) receiver, Estimated VTEC Comparison

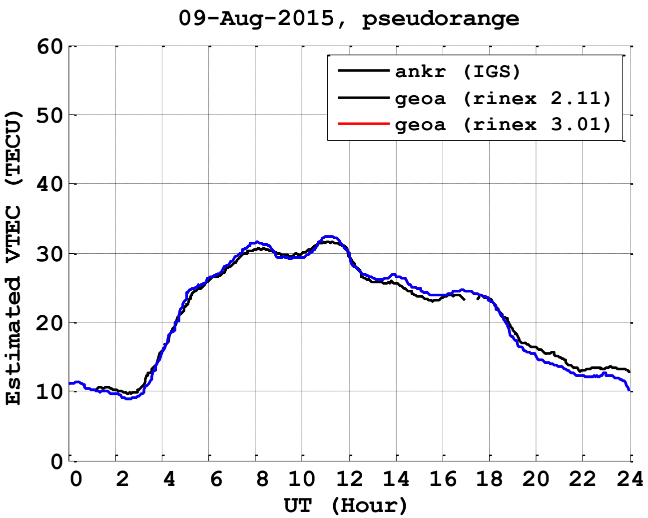
TEC from pseudorange | **TEC from phase**

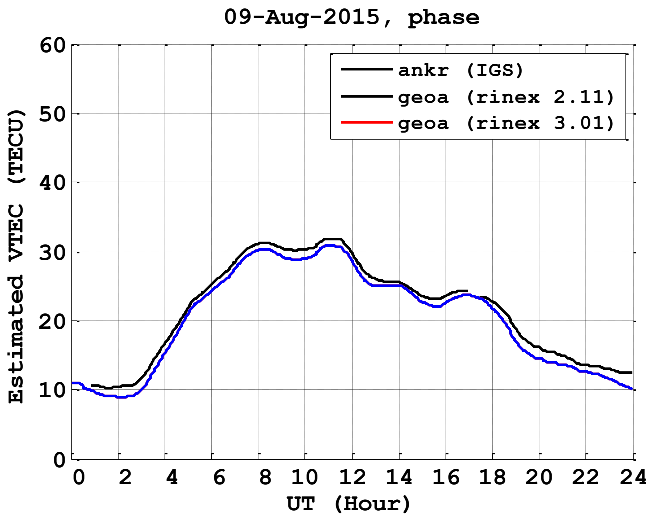
Rinex 2.11





ankr vs. geoa



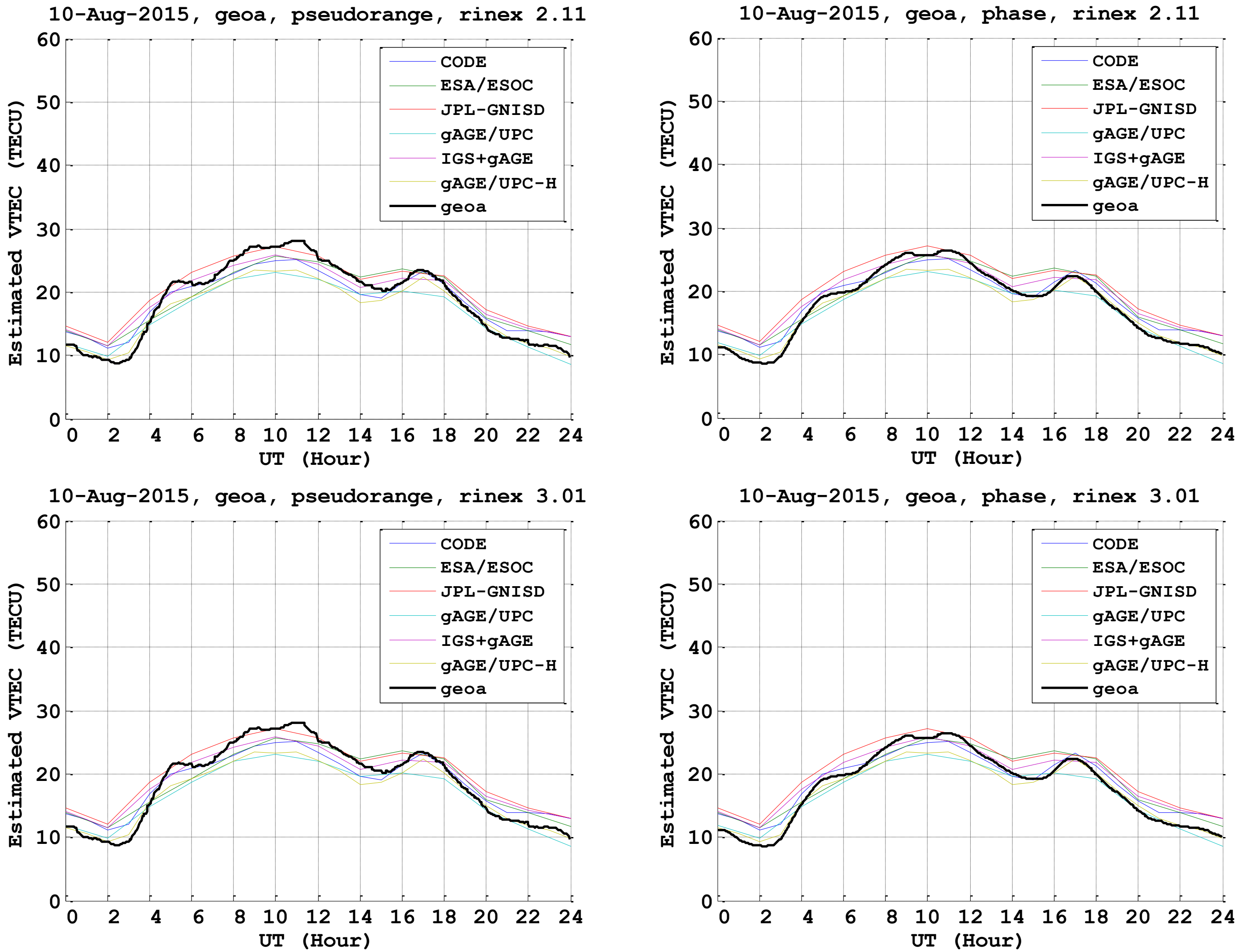


10 August 2015, geoa receiver, Estimated VTEC Comparison

TEC from pseudorange **TEC from phase**

Rinex 2.11

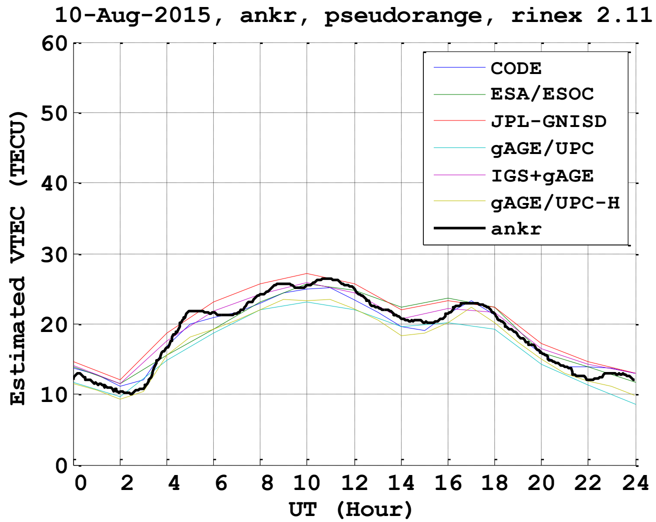
Rinex 3.01

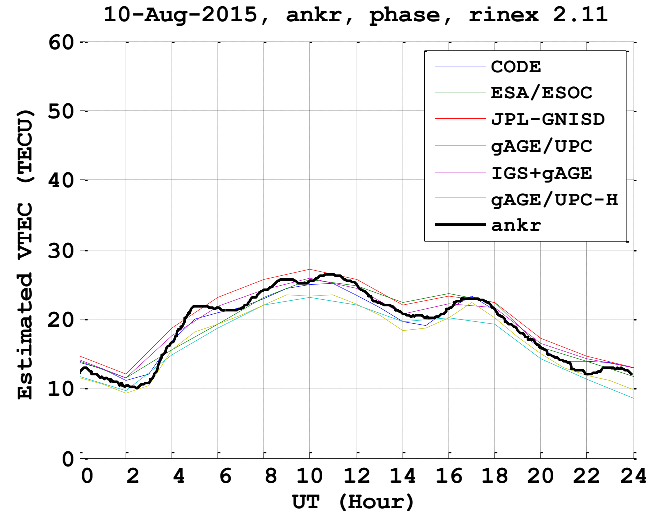


10 August 2015, ankr (IGS) receiver, Estimated VTEC Comparison

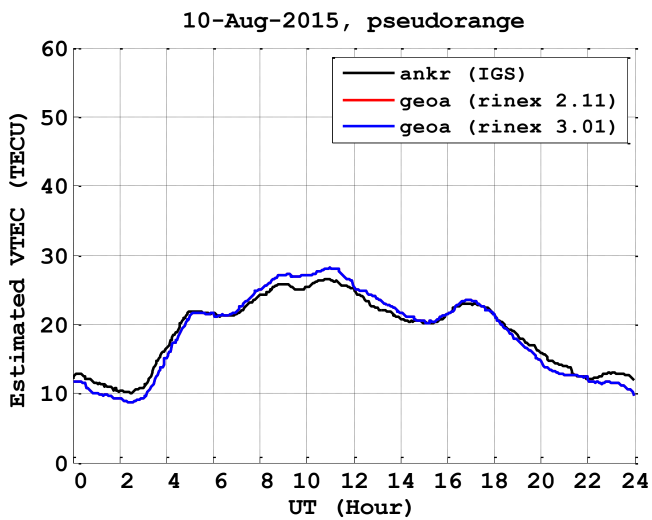
TEC from pseudorange | **TEC from phase**

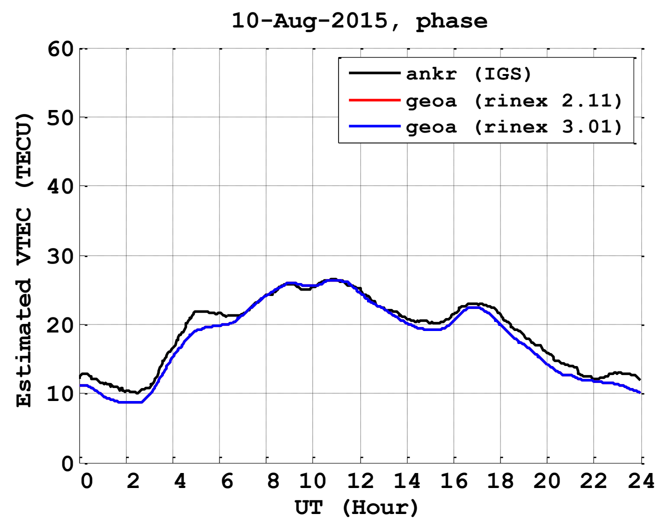
Rinex 2.11





ankr vs. geoa



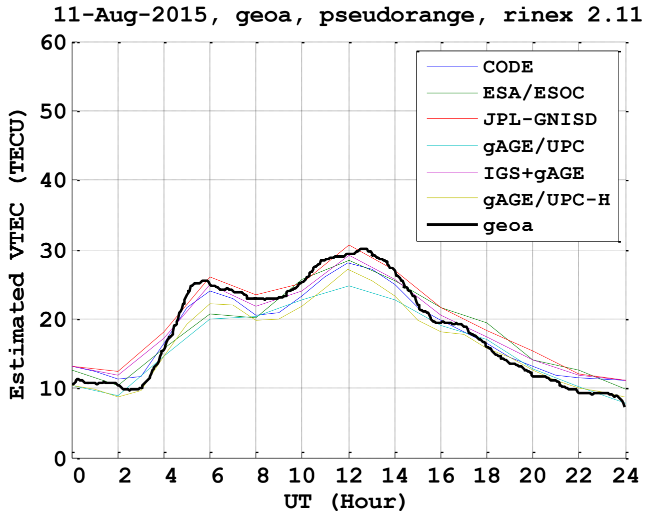


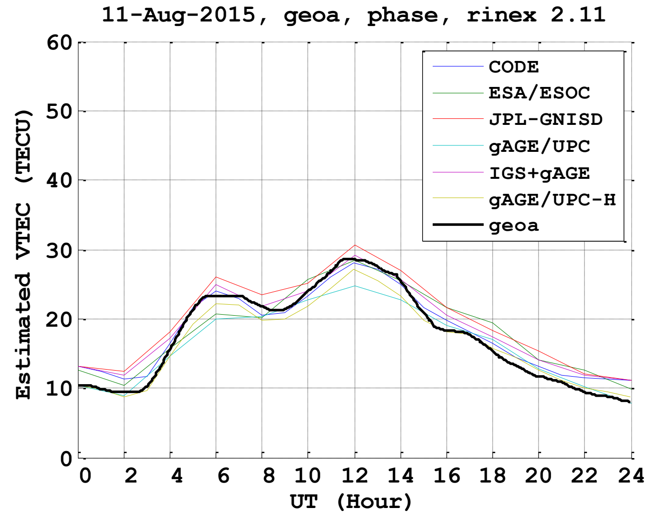
11 August 2015, geoa receiver, Estimated VTEC Comparison

TEC from pseudorange

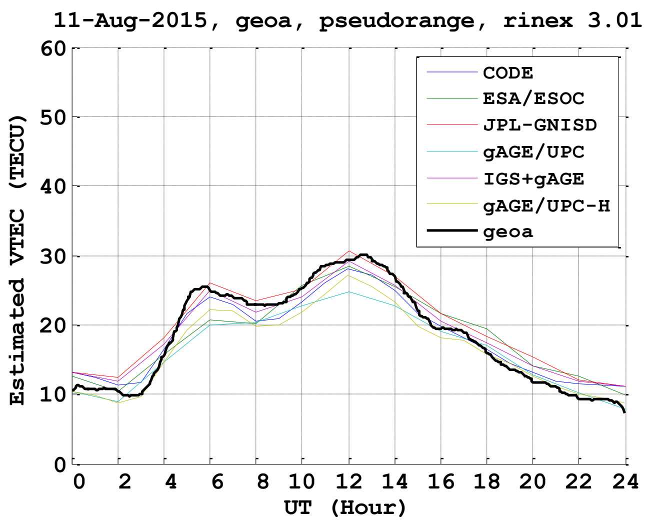
TEC from phase

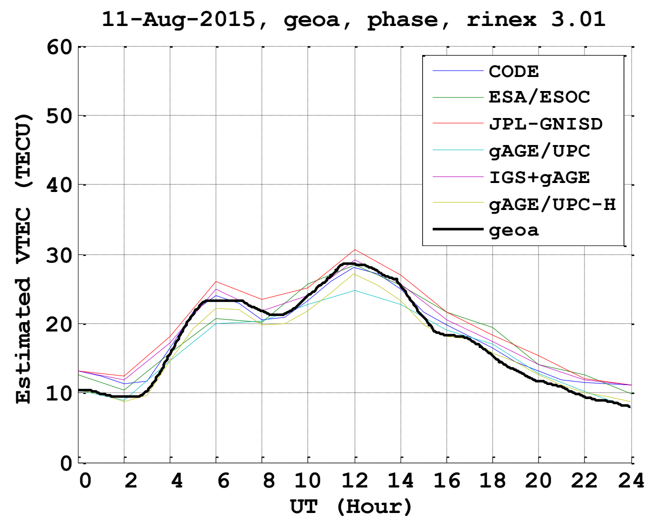
Rinex 2.11





Rinex 3.01

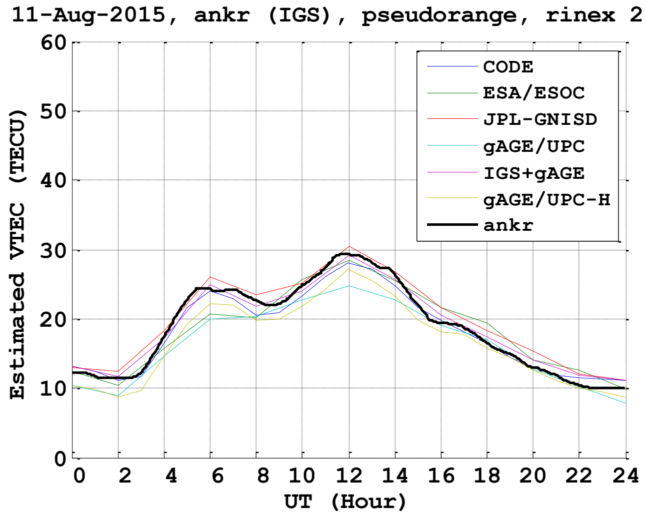


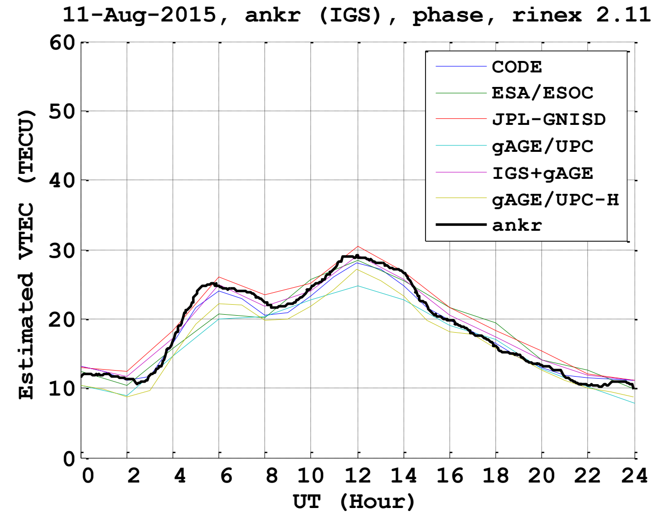


11 August 2015, ankr (IGS) receiver, Estimated VTEC Comparison

TEC from pseudorange | **TEC from phase**

Rinex 2.11





ankr vs. geoa