TIRO

Topside **I**onosphere **R**adio **O**bservations from multiple LEO-missions

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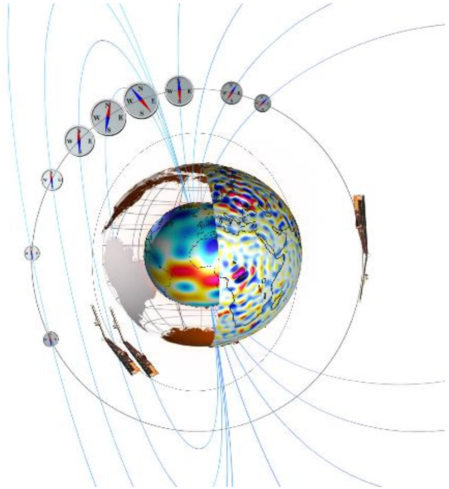

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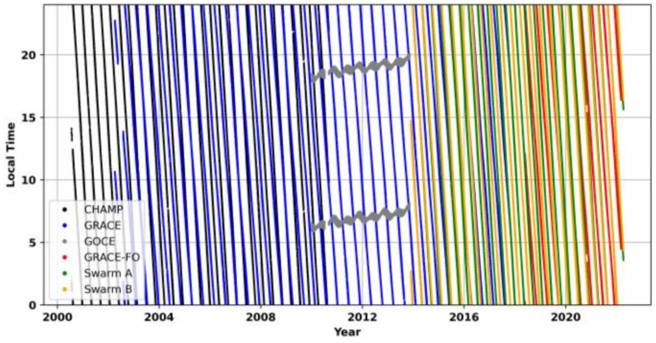
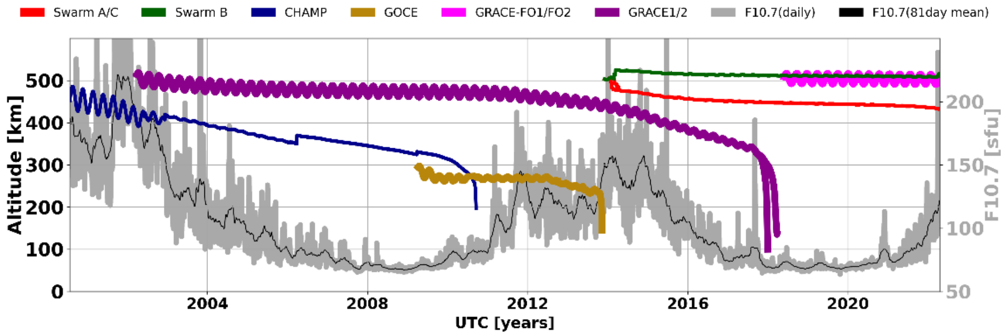
Orbit characteristics

Extending Swarm topside observations with:

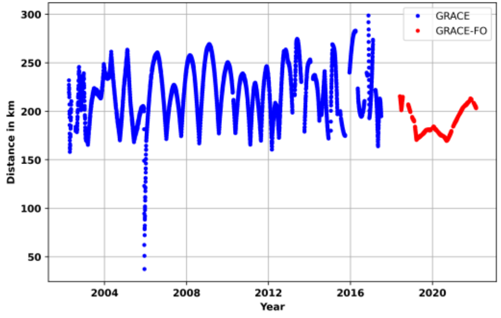
- GPS derived Total Electron Content (TEC)
  - CHAMP
  - GRACE A/B
  - GRACE-FO 1/2
- Electron density from inter satellite K-band
  - GRACE
  - GRACE-FO

Local time evolution





GRACE(-FO) inter-satellite distance



TEC computation from dual-frequency GPS

Slant TEC is derived using the GPS carrier phase observations (L_1, L_2) and calibrated using code observations (P_1,P_2). Differential code biases (DCB) and multi-path corrections are applied to $P_2 - P_1$

$$L_{gf} = L_1 - L_2$$
$$P_{gf}^{cal} = P_2 - P_1 + DCB_T + DCB_R + MP$$

Absolute slant TEC:

$$sTEC = K \cdot (L_{gf} + mn_{arc}(P_{gf}^{cal} - L_{gf}))$$
$$K \approx 40.3\, m^3 s^{-2}$$

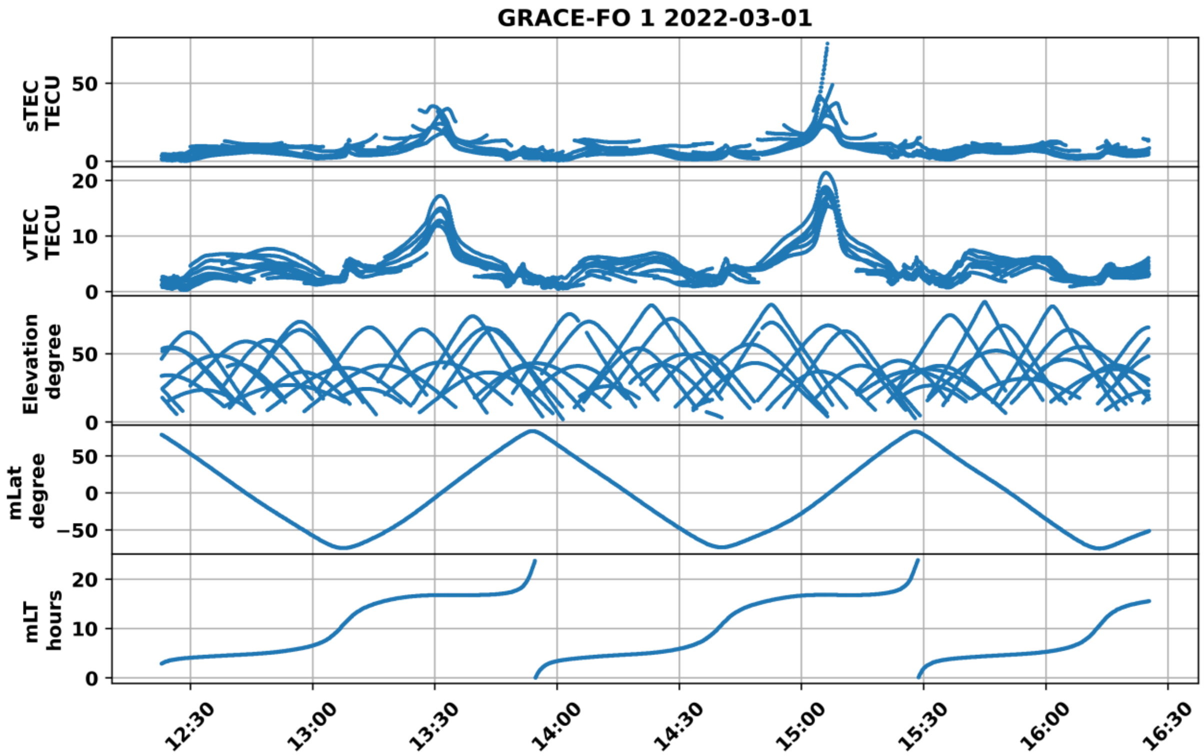
Vertical TEC is obtained using an elevation dependent mapping function $M(\epsilon)$.

The receiver DCB must be estimated. The following system is solved using least squares:

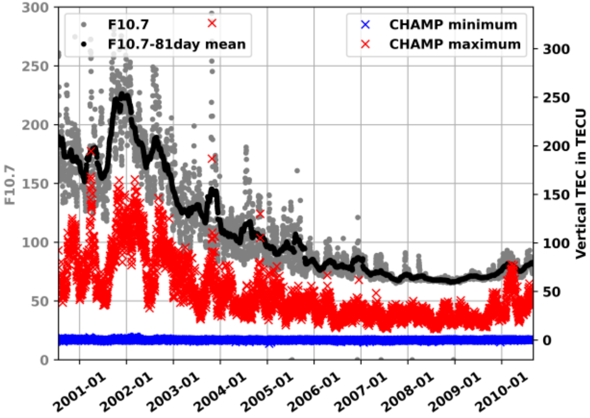
$$M(\epsilon_i) \cdot (sTEC_i + DCB_R) = M(\epsilon_j) \cdot (sTEC_j + DCB_R)$$

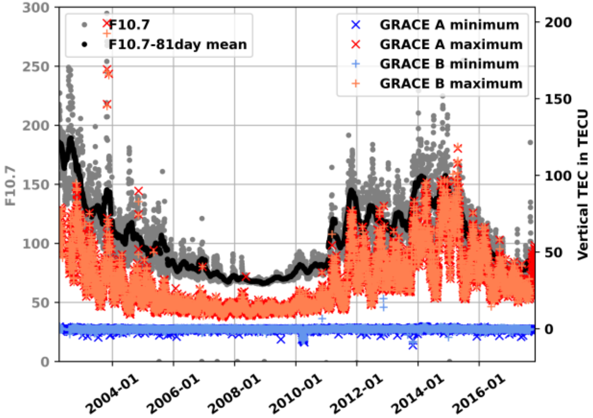
L_i: phase measurement in m, P_i: code measurement in m, DCB_R: receiver $P_1 - P_2$ DCB, DCB_T: transmitter $P_1 - P_2$ DCB, MP: near-field multi-path, mn_{arc}: mean over a continuous arc of observations (no gaps, cycle-slips, or tracking issues)

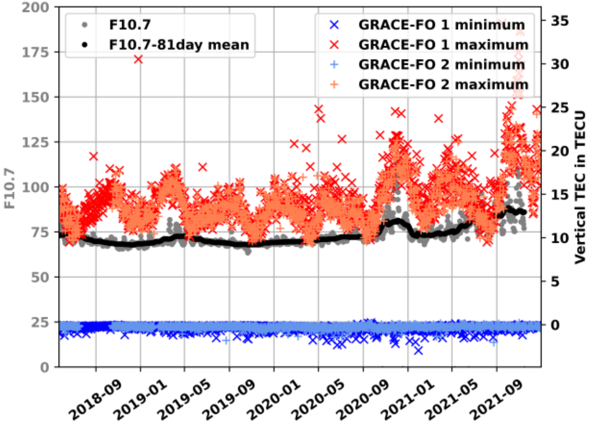
TEC time-series



Quality indication CHAMP

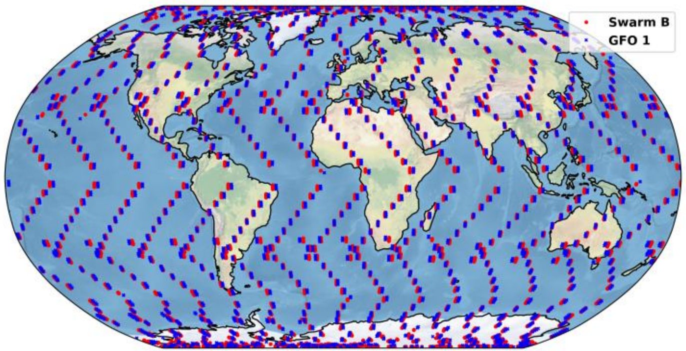




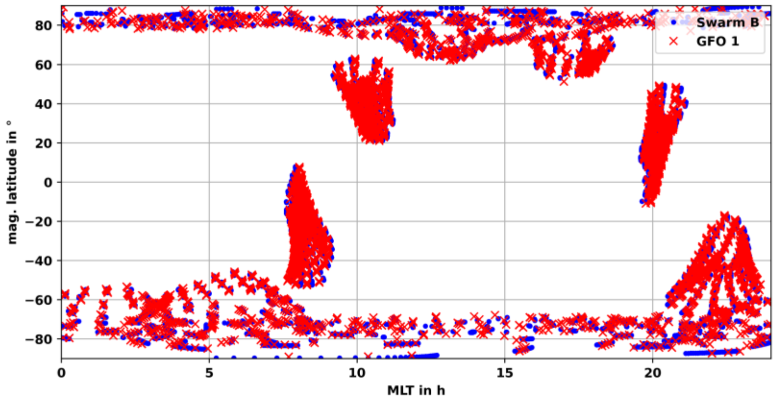


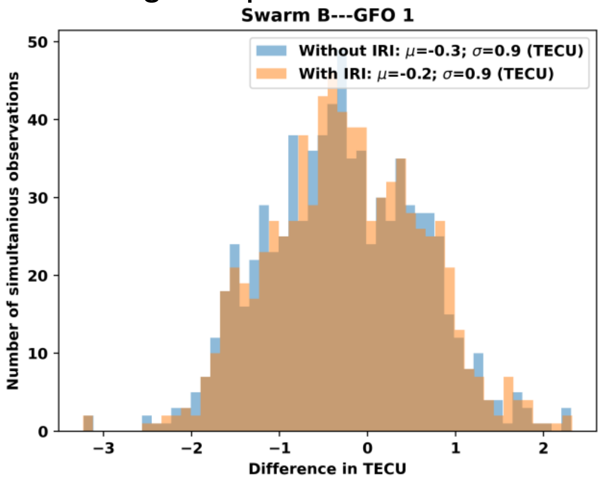
Correlation between F10.7 and max TEC (both as 81d mean):
0.93 (CHAMP), 0.81 / 0.82 (GRACE A / GRACE B), 0.74 /0.71 (GRACE-FO 1 / GRACE-FO 2)
Local time dependent oscillations in TEC.

TEC conjunctions



Swarm B and GRACE-FO 1 conjunctions: counterrotating December 2019. Less than 20 km difference in altitude.
Compensated for differences in TEC due to altitude differences using vertical TEC from IRI-2016.
Also serves for electron density validation (Swarm B Langmuir probes – GRACE-FO KBR)





TEC conclusions

- Highly consistent time series
- Robust estimation of receiver DCB
- Excellent agreement during conjunctions with standard deviations below 2.4 TECU (below 1 TECU possible, if solar activity is low).

	CHAMP GRACE A	CHAMP GRACEB	GRACE A Swarm A	GRACE A Swarm B	GRACE-FO 1 Swarm A	GRACE-FO 2 Swarm B
Mean (TECU)	-0.3	-0.4	0.3	0.1	0.9	0.3
Std. (TECU)	2.4	2.1	1.1	1.0	1.2	0.7

KBR electron density estimation

KBR provides dual-frequency phase measurements on K (24 GHz) and Ka (32 GHz) frequency. The ionospheric phase advance for Ka is stored in the $Iono_{corr}$ variable

$$rTEC = Iono_{corr} \cdot \frac{f_{Ka}^2}{K}$$

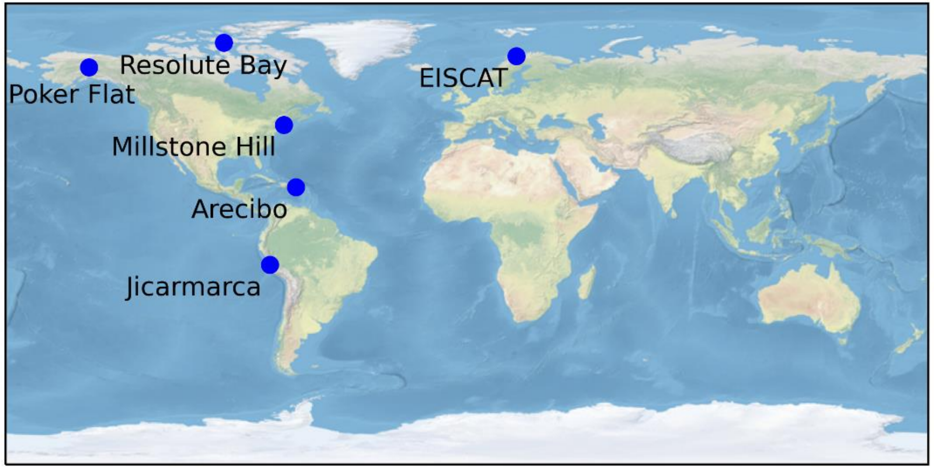
$$K \approx 40.3\, m^3 s^{-2}$$

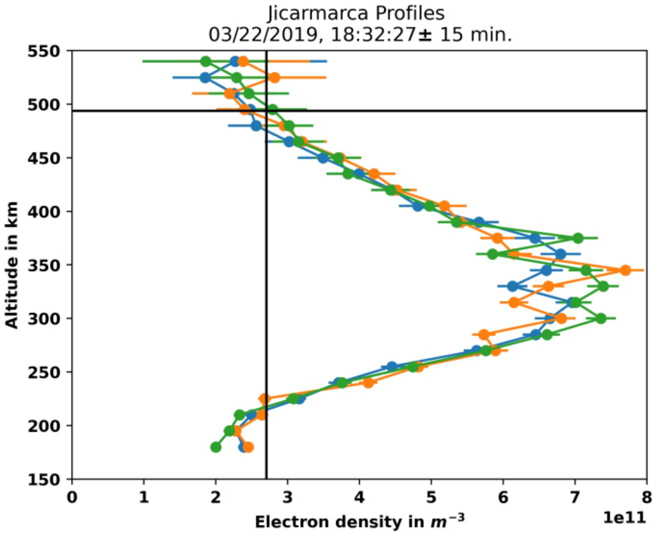
Since the distance d between the satellites is only 200 km, this may be used to approximate the local electron density

$$rNe = rTEC \,/\, d$$

Absolut calibration needs to be provided externally (e.g. IRI-2016 model). Arbitrary offset in $Iono_{corr}$ constant if KBR is not interrupted.

KBR validation against radars





Criteria are $\pm$ 5° in lat/lon, $\pm$ 15 min, at least one radar observation within 20 km altitude of the satellite. Radar observations are interpolated between altitudinal sampling points using a quadratic function fitted on $\log10(Ne)$ on radar observations $\pm$ 100 km h_{sat}.

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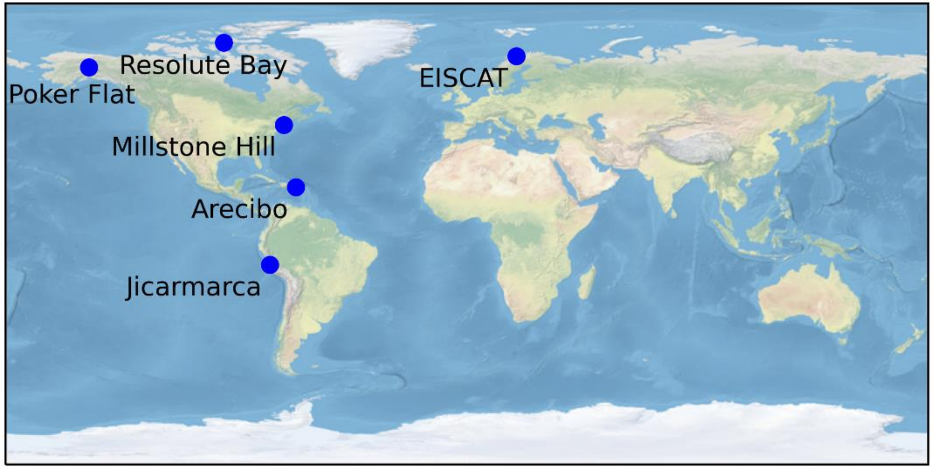

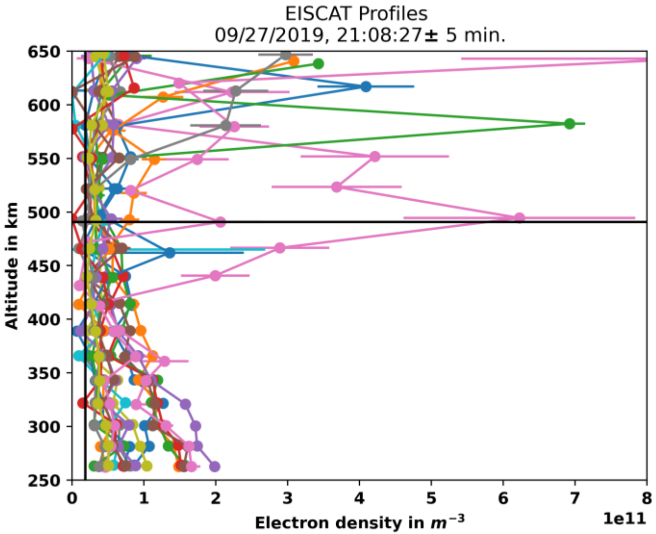

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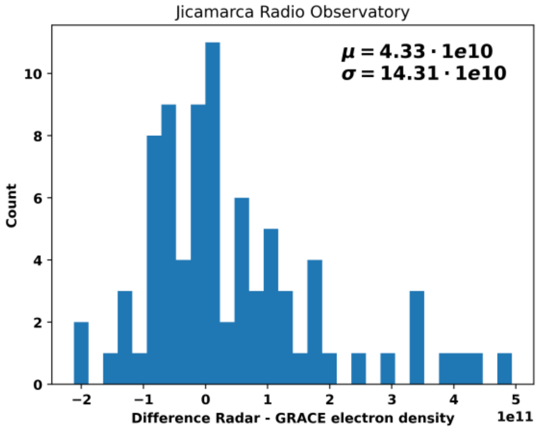
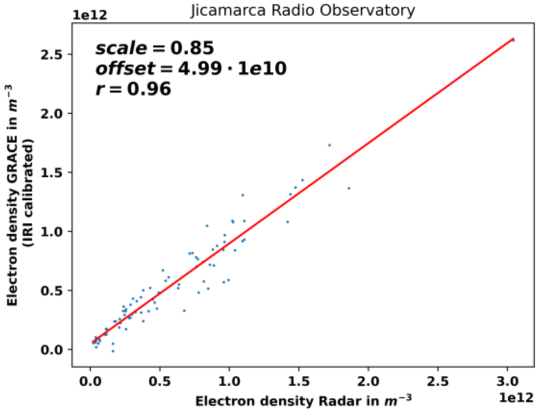
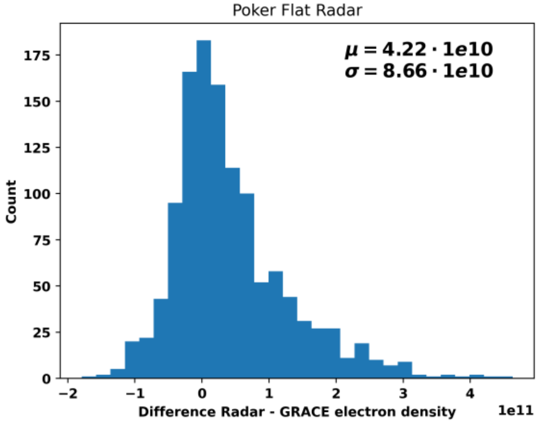
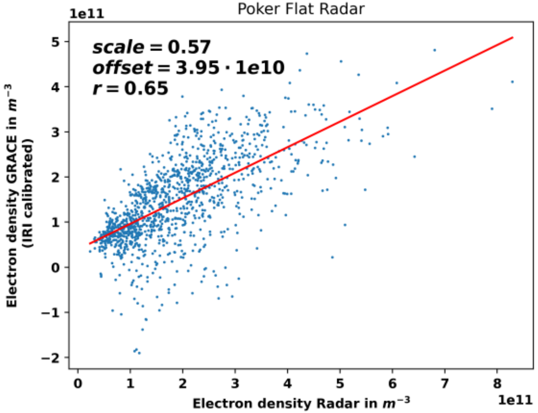








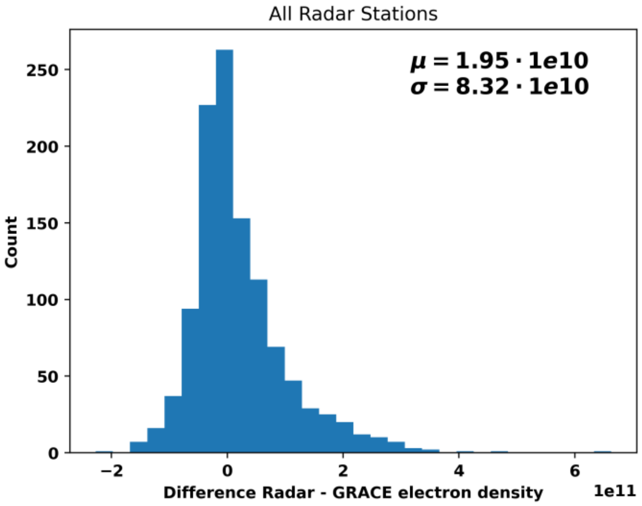
μ: mean calibration difference
σ: standard deviation of calibration difference

Best fit for low-latitude stations, e.g., Jicarmarca.

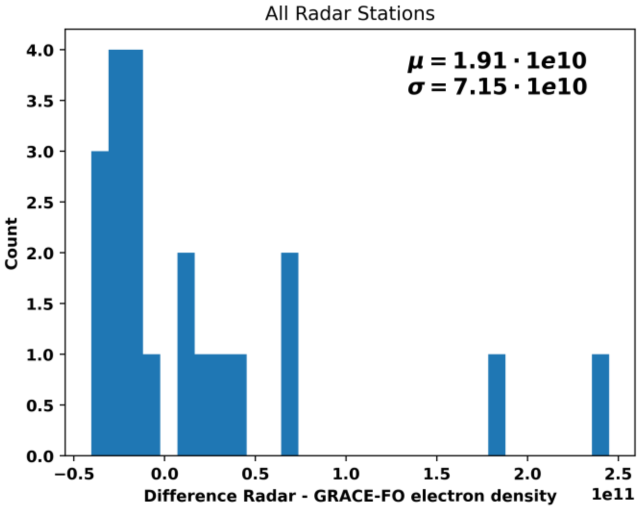
Challenging for near polar stations. Irregular profiles and large scatter in higher altitudes, e.g. Poker Flat.

KBR validation against radars

GRACE



GRACE-FO



Small mean offset and standard deviation within the observational limits of the radar systems.

Summary and conclusions

- TEC and electron density time series covering two solar cycles.
- Excellent agreement with Swarm data products.
- #days TEC: 3649, CHAMP
  5613, GRACE 1
  5552, GRACE 2
  1378, GRACE-FO 1 (until 31.3.2022)
  1207, GRACE-FO 2 (until 31.3.2022)
- #days Ne: 4879, GRACE
  1202, GRACE-FO (until 31.3.2022)

- Data available at ftp://isdcftp.gfz-potsdam.de
  and soon via ESA at http://swarm-diss.eo.esa.int