2nd Order Ionospheric Correction for DORIS and GPS Data

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Rationale (1)

• Not applying 2nd & 3rd order ionosphere effects have been shown to affect (bias) GPS-based velocity determinations compared to runs without these effects (*e.g. Petrie et al., J Geophys Res., 115(B3), B03417, doi:10.1029/2009jb006677*).

PETRIE ET AL.: HIGHER-ORDER IONOSPHERIC EFFECTS ON GPS

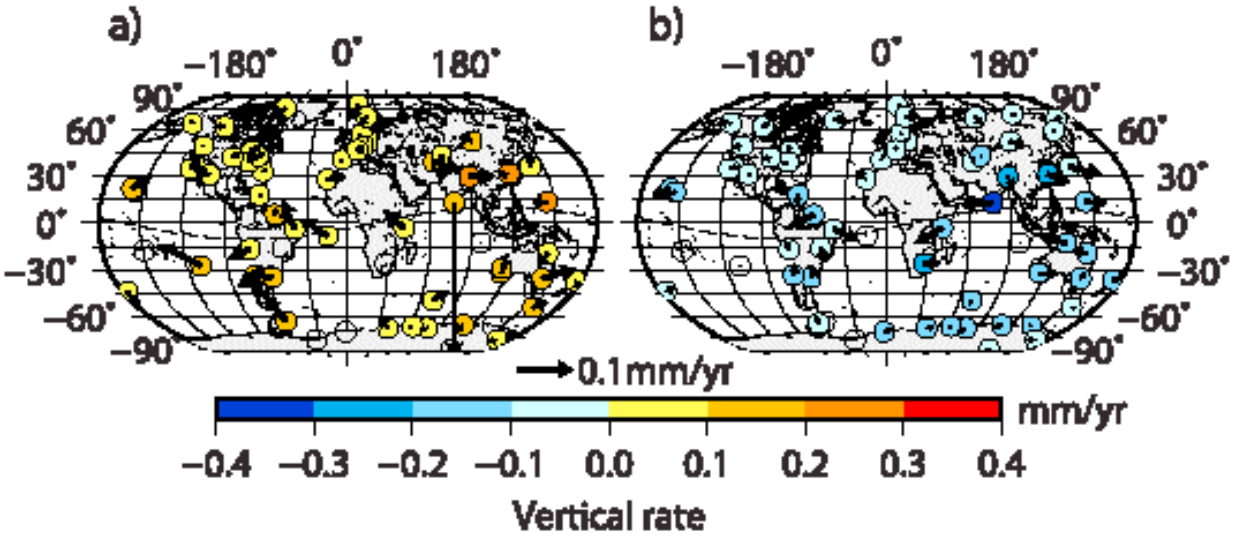


Figure 5. (a) Velocity differences over the period 1996–2000 (N-IG). (b) Velocity differences over the period 2001–2005 (N-IG). Arrows represent motion in plan. The geomagnetic equator is shown as a dashed line. Sites shown have data spanning at least 4.5 years of the 5 year period, with a minimum of 2.5 years of data. Open circles show sites processed that did not meet these criteria.

Rationale (2)

• Not applying 2nd & 3rd order ionosphere effects also appears to cause a reference frame effect, particularly in the Tz component, correlated with the solar cyle.

(*e.g. Petrie et al., J Geophys Res., 115(B3), B03417, doi:10.1029/2009jb006677*).

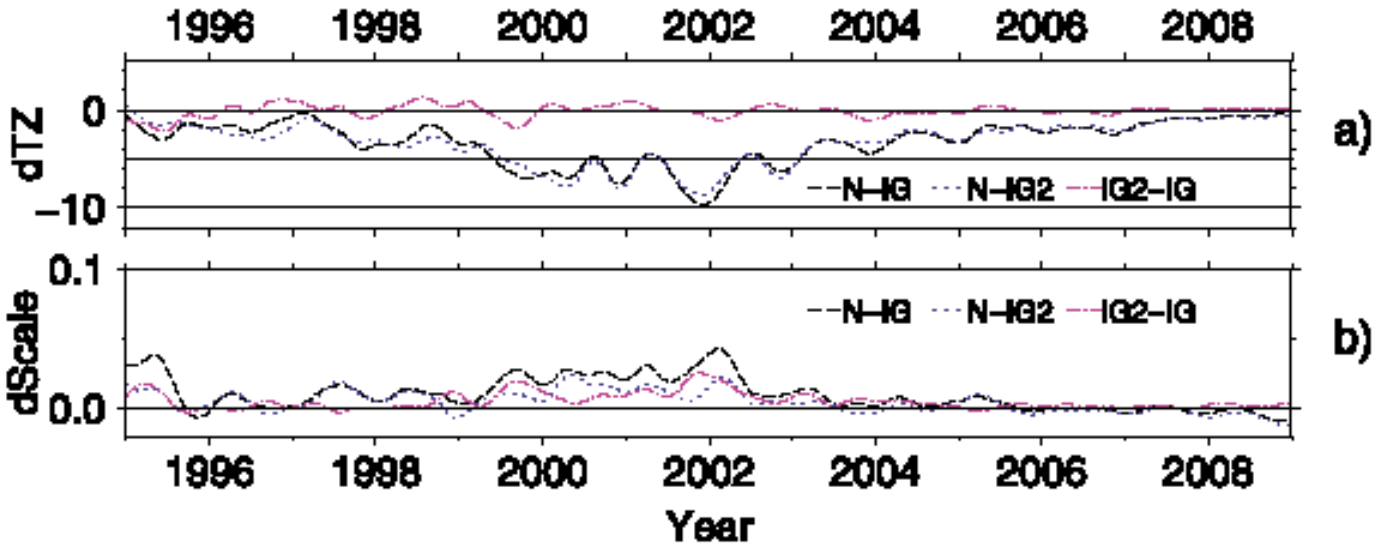
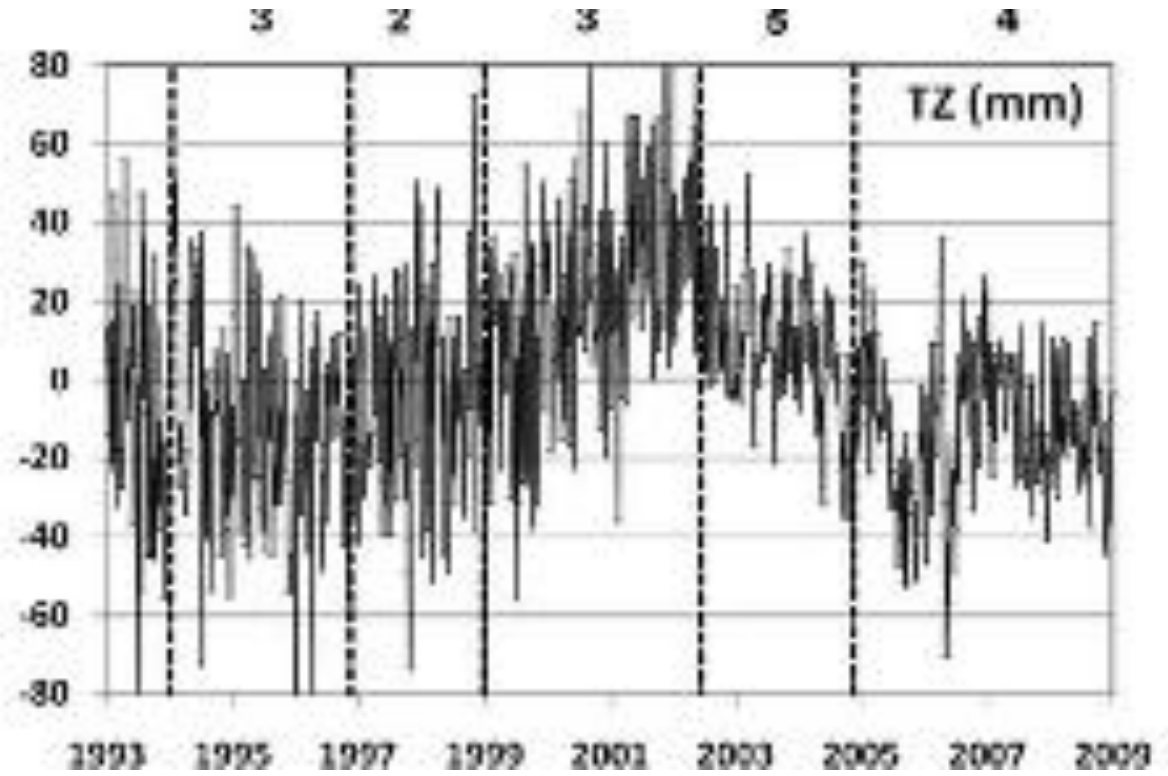


Figure 4. (a) Effect on the *Z* translations between solutions when modeling the third-order term (mm). (b) Effect on the scale of modeling the third-order term (ppb). For Figures 4a and 4b, three comparisons are shown: N-IG, the effect of modeling second- and third-order terms (black dashed line); N-IG2, the effect of modeling the second-order term only (blue dotted line); and IG2-IG, the effect of modeling the third-order term (magenta dot-dashed line). All data are shown with 90 day Gaussian smoothing.

Rationale (3)

• A large signal in Tz was observed in the IDS-3 solution developed for ITRF2008 (Valette et al., *Adv. Space. Res*., 2010).



2nd ORDER IONOSPHERIC CORRECTION (GPS): Possible effect on station positions

(Manuel Hernandez-Pajares et al. JGR, August 2007, as quoted in E. Petrie's 2010 PhD thesis, Newcastle)

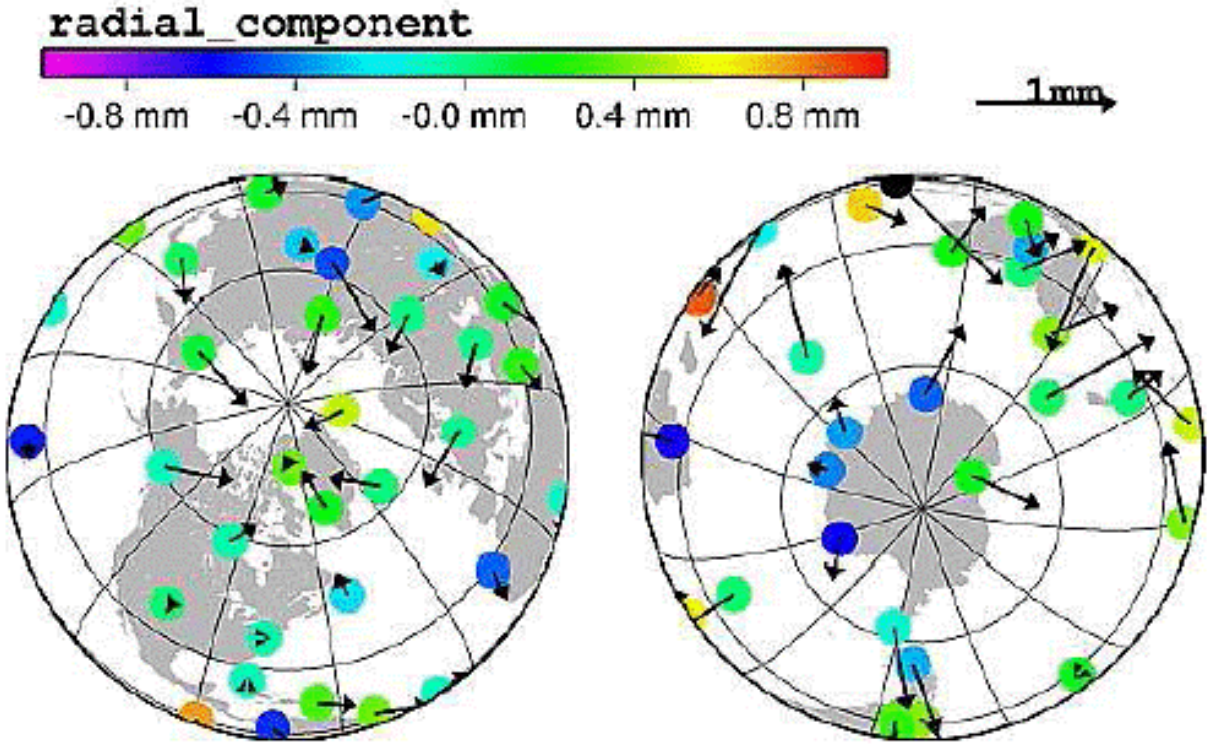
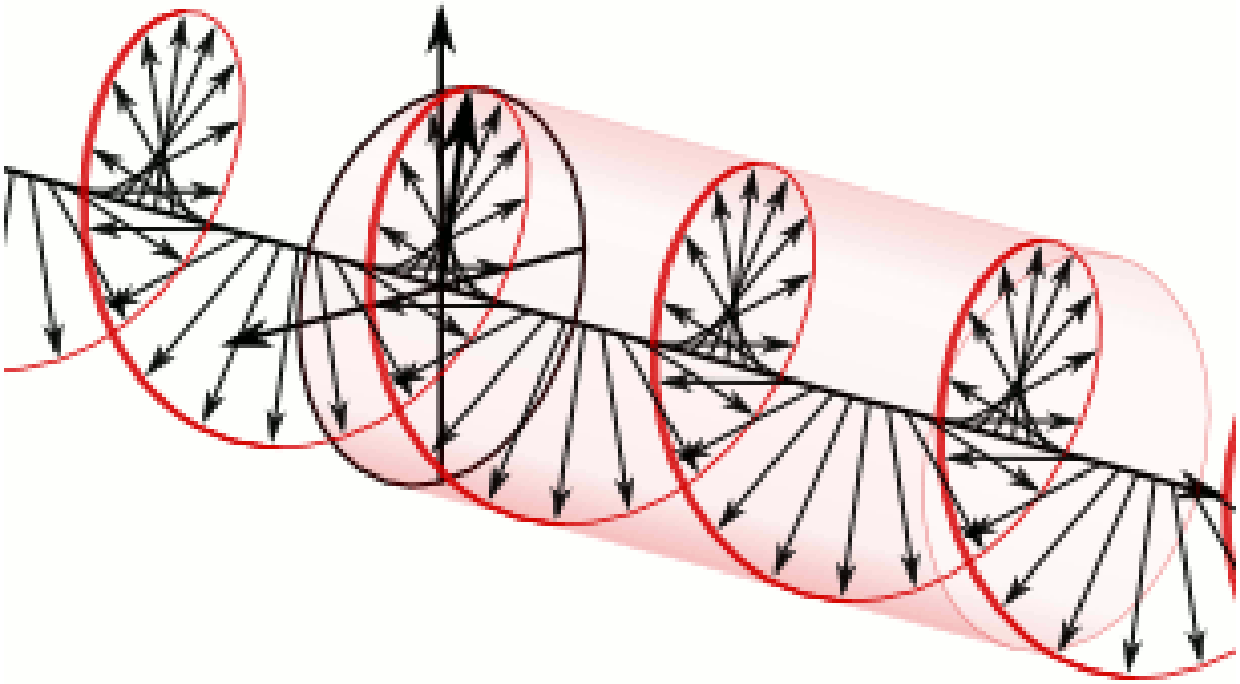


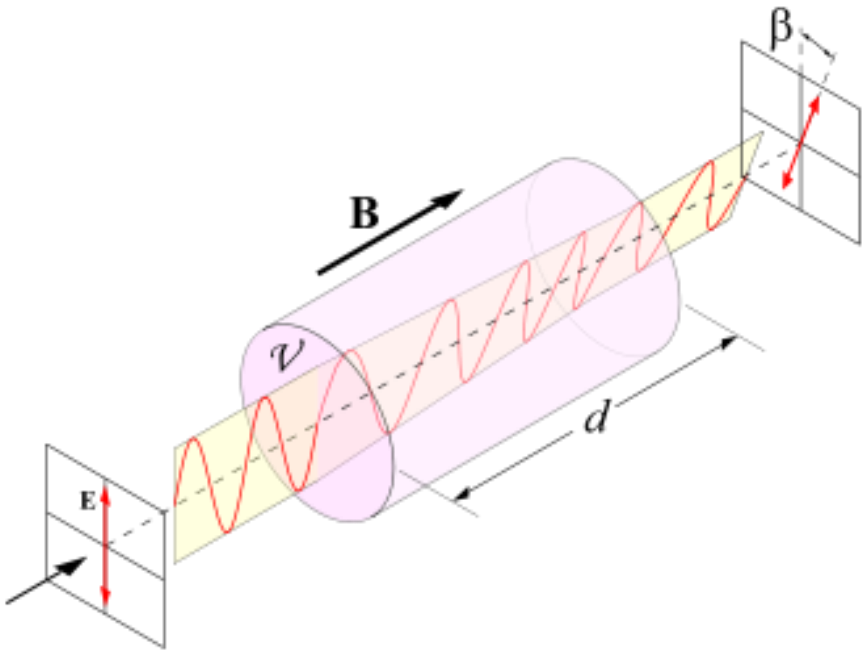
Fig. 27 Polar projections of data in Fig. 26. "In this case, receivers with at least 100 days of data are plotted. The northward shift of the high-latitude receivers is confirmed" (Hernández-Pajares et al., 2007, Figure 16).

Faraday Rotation Changes the Phase and Frequency of Circularly Polarized Radio Waves by Adding an Increasing Extra Twist to their Electric and Magnetic vectors



Source: Wikipedia, Creative Commons

Faraday Rotation of Radio Waves in an Ionized Medium Subject to an External Magnetic Field



β = polarization plane rotation angle; **E** = wave electric field vector; **B** external magnetic field; **ν** = Verdana constant, proportional to **nB.d/f³** (where **n** is the free electron density, **f** is the frequency and **d** is the unit vector along the direction of propagation).

(Picture: Wikipedia, Creative Commons)

2nd ORDER IONOSPHERIC CORRECTION

- Small correction $\delta\phi$, $\delta\rho$**dot** to the received phase and frequency.
- Simplified expressions commonly used -- the exact formulas contain line integrals along the waves' path:

$$\delta\phi \approx k_\phi \, 1/f^3 \, STEC \, (B \cos \alpha)$$

for **GPS** phase. Up to 1-2 cm in Lc -- usually a few mm.

$$\delta\rho dot \approx k_{\rho dot} \; 1/f^3 \{ d/dt \, STEC \, (B \cos \alpha) + STEC \, d/dt \, (B \cos \alpha) \}$$

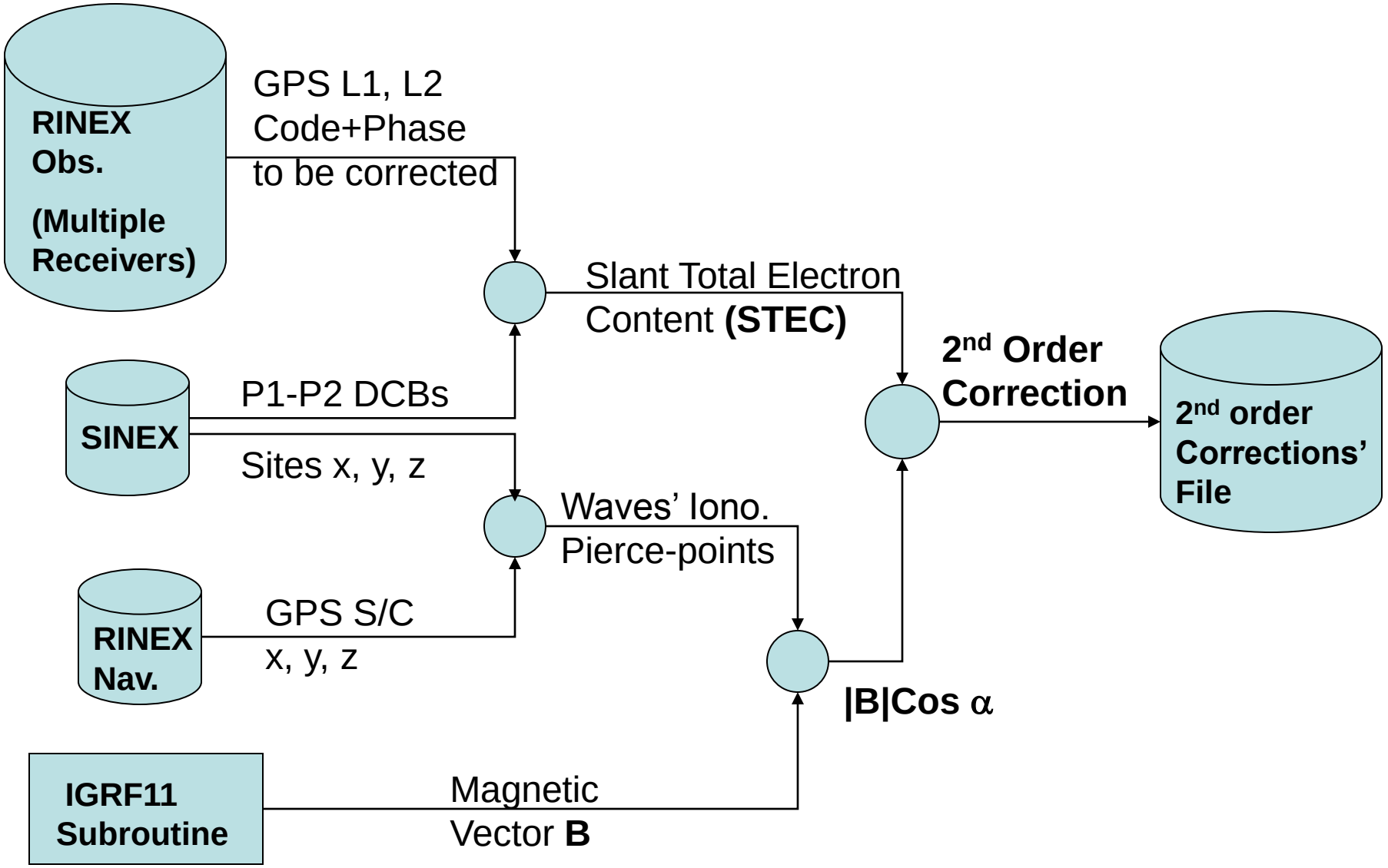
for **DORIS** 2GHz Range-rate (ρ**dot**) – mostly < 100 μm/s.

- **f** is the carrier frequency of the signal; **STEC**, the total free electron content along path of radio waves; **B** the geomagnetic field induction vector; α the angle of **B** with the direction of propagation; $\mathbf{K}_\phi$ and $\mathbf{k}_{\mathbf{rdot}}$ are constants for phase and Doppler. **B,** α are calculated at the intersection (piercing points) of the rays with a 2-D shell at 450 km (in, roughly, the thickest part of the ionosphere).

2nd ORDER CORRECTION: SOFTWARE

- Two FORTRAN programs developed by Oscar L. Colombo:
- **(I) "F3iono"**: for GPS, to calculate the 2nd order correction to Lc (L1 corrected for 1st order effect), using:
- The same GPS phase and code data to find the STEC (Ch.9, IERS Conventions 2010).
- Subroutine "IGRF11SYN" to calculate **B** according to the International Geomagnetic Reference Fields from 1900 to 2015 (British Geological Survey, for IAGA WG V-MOD, December 2009).
- Broadcast orbits from GPS Rinex Navigation files.
- Site coordinates and P1-P2 Differential Code Biases (DCBs) from IGS Sinex files.
- Corrections written to a file, ordered: first by epoch, then by GPS site.
- Tested by comparing results to those kindly provided by E. Petrie (Newcastle U) using the same GPS data.

Program F3IONO (GPS) Data Flow

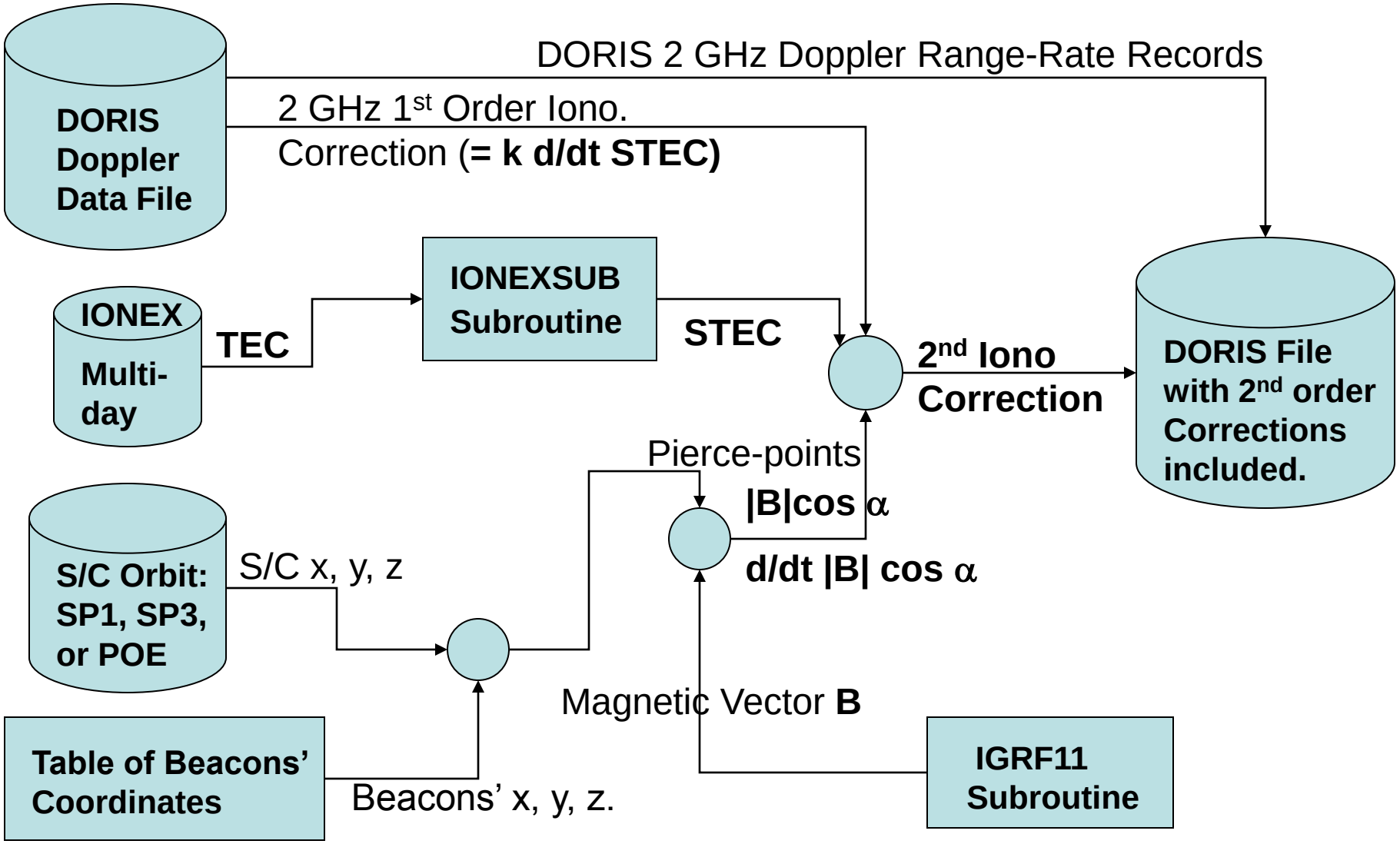


2nd ORDER CORRECTION: SOFTWARE

- **(II) "F3doris"**: for DORIS Range-Rate (2 GHz).
- Developed and tested with DORIS range-rate data from one cycle of TOPEX (solar max) and one of JASON 2 (solar min).

- **STEC** from IGS Combination GIM in Ionex format.
- **d/dt STEC = k/f x (1st order correction to 2 GHz range-rate)**, where **k** is a constant, from DORIS range-rate files.
- **B** from the IGRF11 subroutine, **d/dt B cos** α obtained by numerical differentiation.
- Coordinates of DORIS ground beacons, from a table.
- Coordinates of a satellite with DORIS receiver, from SP1, SP3, or POE orbit files.
- Corrections written to a file, and arranged: first by epoch (in same order as in Doppler data file), then by beacon site.

Program F3DORIS Data Flow



2nd ORDER CORRECTION DORIS: SOME EARLY RESULTS

- With TOPEX in 2002 (near solar max), ~60% of the time the correction was above the data truncation level of 1 μm/s
- With JASON 2 in 2010 (end of solar min), ~30% of the time the correction was above that level
- Preliminary testing by N. Zelensky (SGT Inc.) has shown sub-mm changes in JASON 2 ephemerides.
- Further testing needed to see if this correction has any significant systematic effects on orbits/reference frame, e.g. with the roughly 11-year period of the solar cycle.