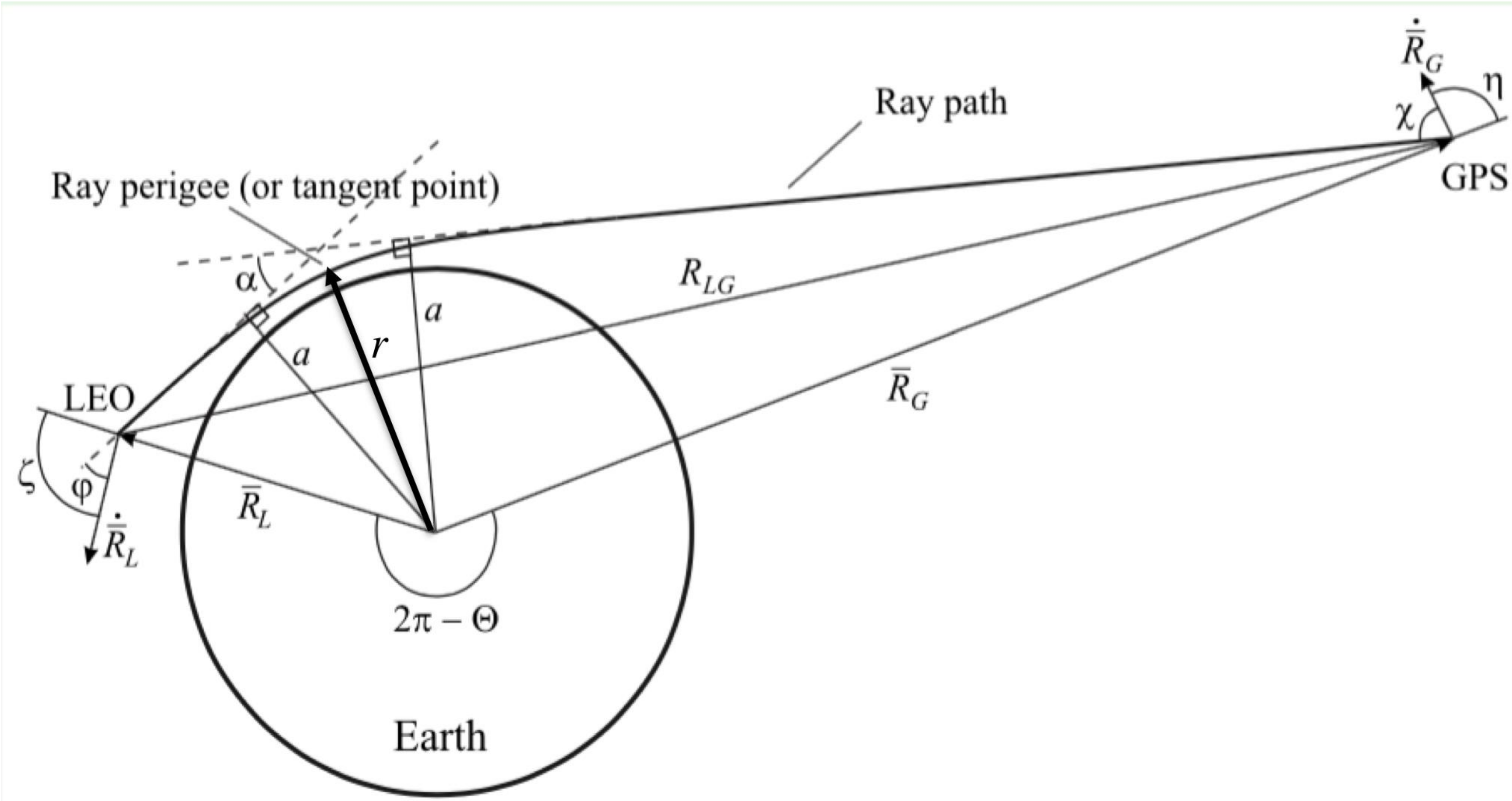
Honing in on atmospheric excess phase computation for Radio Occultation



Doug Hunt, UCAR
Josef Innerkofler, Wegener Center
Sergey Sokolovskiy, UCAR

Introduction

This talk is motivated by a visit from Josef Innerkofler of the Wegener Center in Graz, Austria to UCAR in order to learn about excess phase processing and finalize the implementation of the WEGC excess phase code, a part of their Reference Occultation Processing System (rOPS). This visit sparked good collaboration and learning on both sides, which I'll summarize here.

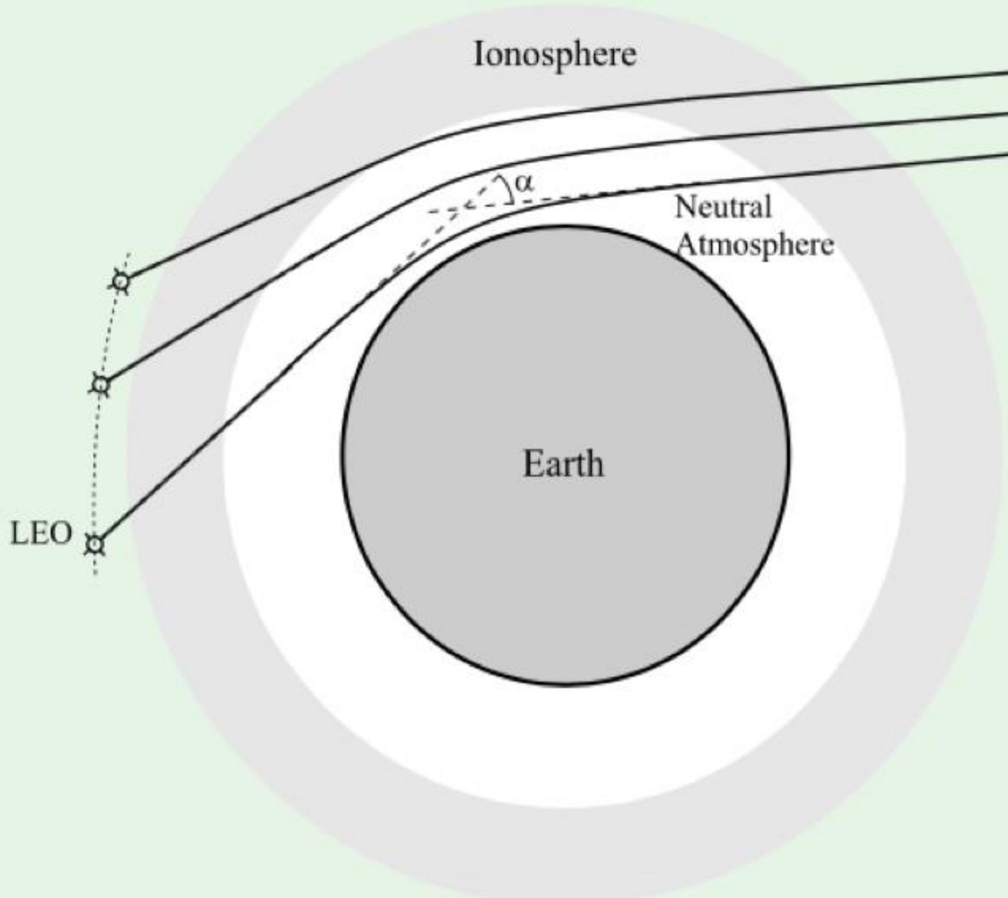
First, I'll situate excess phase processing in the radio occultation processing chain.

Next, I'll dive into the details, focusing on one occultation from the GRACE mission and discussing many processing details and how big an effect they have.

Finally, I'll show some results of the comparison between the UCAR CDAAC excess phase code and the rOPS (WEGC Reference Occultation Processing System) code, the result of Josef's 6-month stay at UCAR.

Radio Occultation processing overview

The GPS radio occultation principle



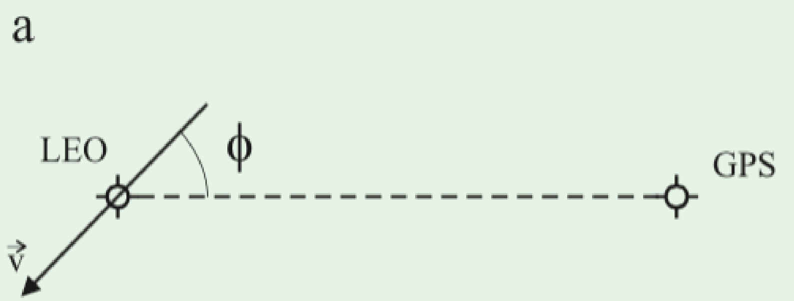
GPS = Global Positioning System
LEO = Low Earth Orbiter
α = Bending angle (max ~2°)

Signal frequencies: $f_1 = 1.57542\,\text{GHz}$ & $f_2 = 1.22760\,\text{GHz}$

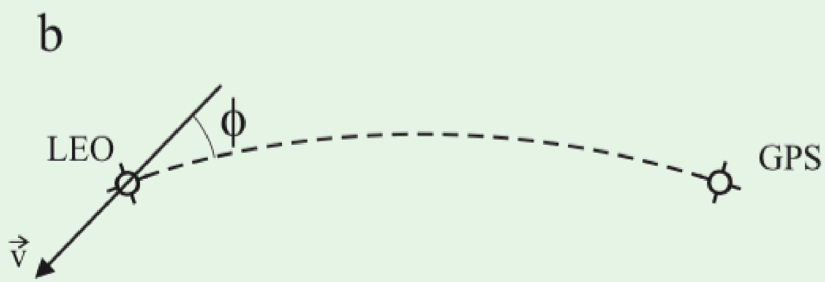
Refractive index of medium: $n \approx 1 + 77.6\frac{p}{T} + 3.73\times10^5\frac{e}{T^2} + 40.3\frac{N_e}{f^2}$

Slides from Syndergaard, 2005

Basic GPS occultation observations



a) The Doppler depends on Φ and $\vec{v}$



b) With bending, the Doppler is different than expected from velocities only

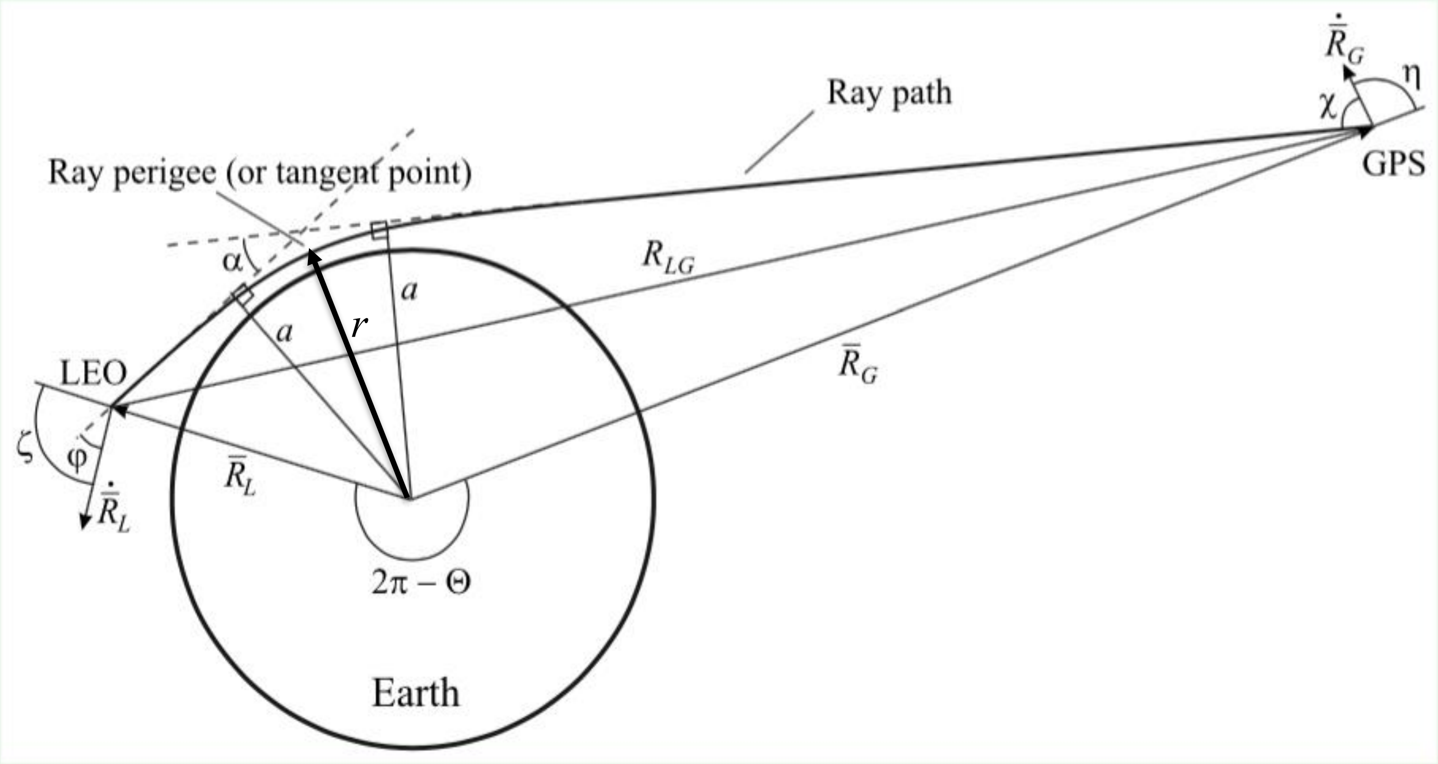
Basic measurement is a phase path (meters): $L = \int_{\mathrm{GPS}}^{\mathrm{LEO}} n \, \mathrm{d}s$

Excess phase (path) is defined as: $\Delta L = L - |\vec{r}_{\mathrm{LEO}} - \vec{r}_{\mathrm{GPS}}|$

Some terms omitted…

We are interested in the phase change: excess Doppler $= \mathrm{d}\Delta L / \mathrm{d}t$

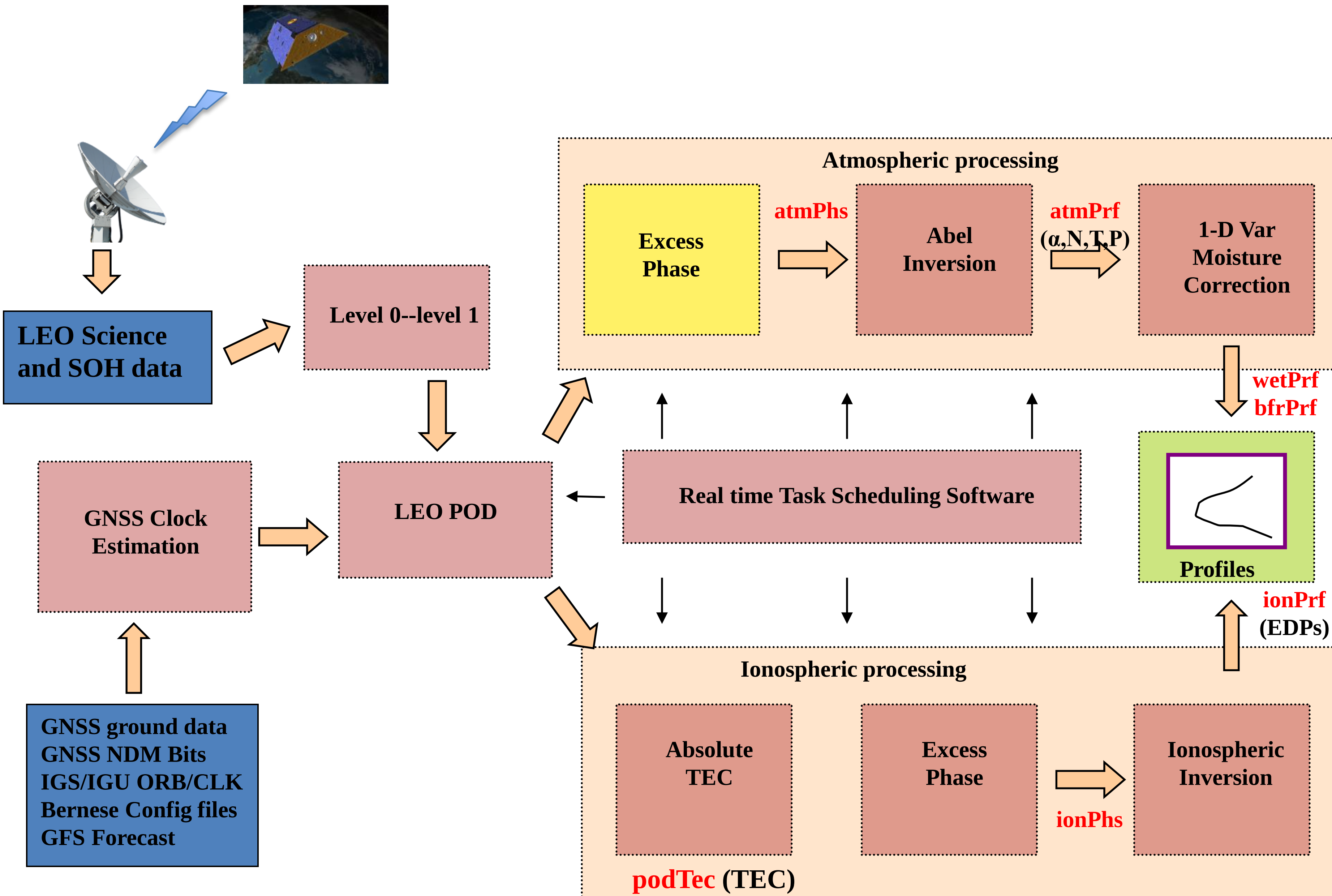
Excess Doppler → bending angle



- Having satellite positions & velocities (from precise orbit determination)
- Having the excess Doppler (from observations)
- Assuming spherical symmetry then determines the impact parameter, a, and subsequently the bending angle, α

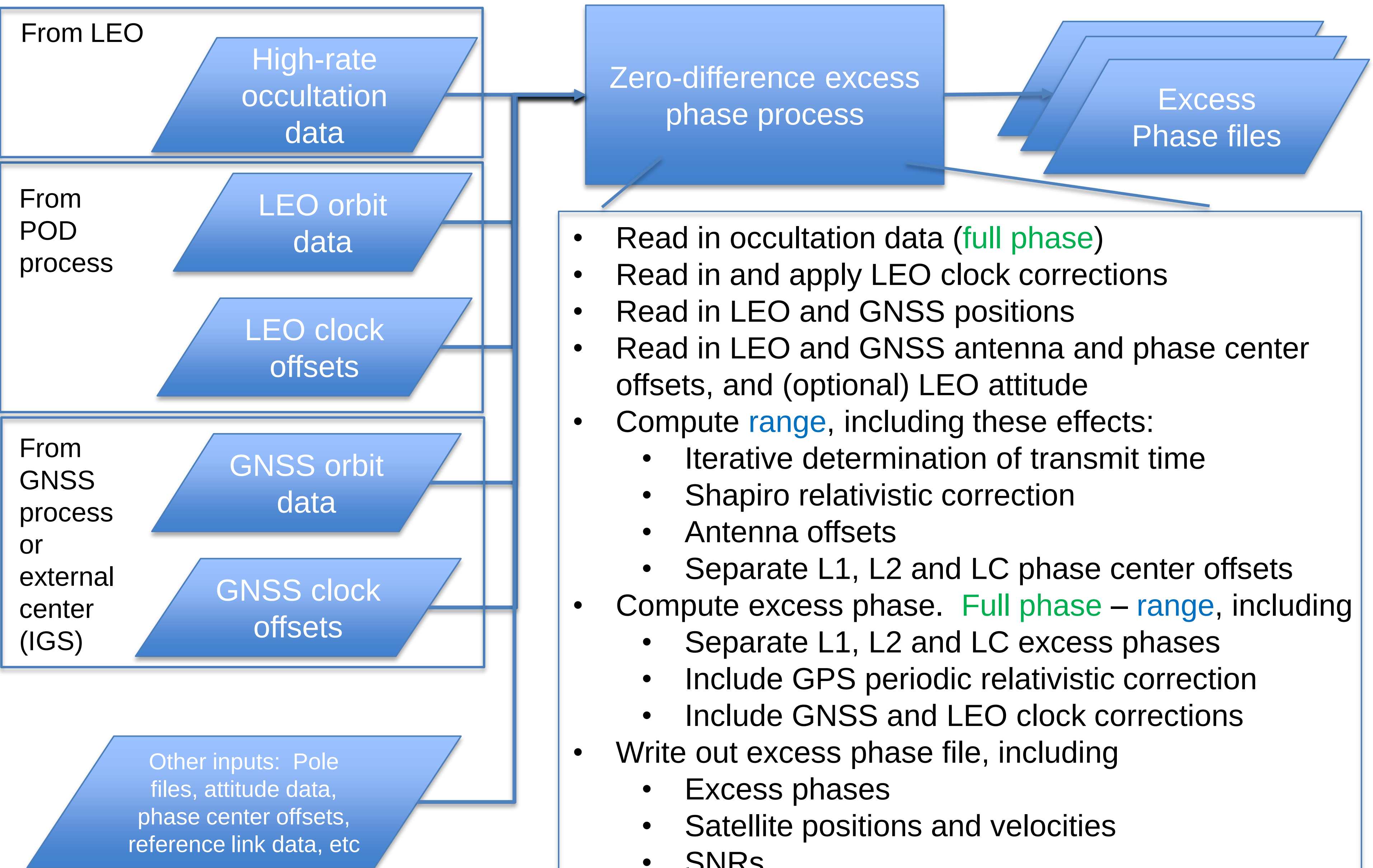
Slides from Syndergaard, 2005

Radio occultation Data Flow



Excess phase processing overview

Excess Phase dataflow



- Read in occultation data (full phase)
- Read in and apply LEO clock corrections
- Read in LEO and GNSS positions
- Read in LEO and GNSS antenna and phase center offsets, and (optional) LEO attitude
- Compute range, including these effects:
  - Iterative determination of transmit time
  - Shapiro relativistic correction
  - Antenna offsets
  - Separate L1, L2 and LC phase center offsets
- Compute excess phase. Full phase – range, including
  - Separate L1, L2 and LC excess phases
  - Include GPS periodic relativistic correction
  - Include GNSS and LEO clock corrections
- Write out excess phase file, including
  - Excess phases
  - Satellite positions and velocities
  - SNRs

Excess phase equation

$$\boxed{L_r^t} = \rho_r^t + c\delta_r - c\delta^t + \lambda N_r^t + \boxed{\delta\rho_{r,atm}^t - \delta\rho_{r,ion}^t} + \rho_{r,corr}^t + \epsilon$$

Raw phase **Excess phase**

- ρ_r^t – Geometric distance between receiver and transmitter
- $c\delta_r, c\delta^t$ – Transmitter and receiver clock biases
- λN_r^t – Integer phase ambiguity
- $\delta\rho_{r,atm}^t, \delta\rho_{r,ion}^t$ – Neutral atmosphere and ionosphere excess phase
- $\rho_{r,corr}^t$ – Modelled effects: relativistic effects, antenna offsets, phase center offsets
- ϵ – Un-modeled errors: thermal noise, multipath, etc.

Note that ρ_r^t is the distance between the transmitter at transmission time $t - \tau$ and the receiver at time t, where τ is the signal travel time from GNSS to LEO.

Note also that δ_r is the receiver clock bias at time t (GPS time) and δ^t is the transmitter clock bias at time $t - \tau$.

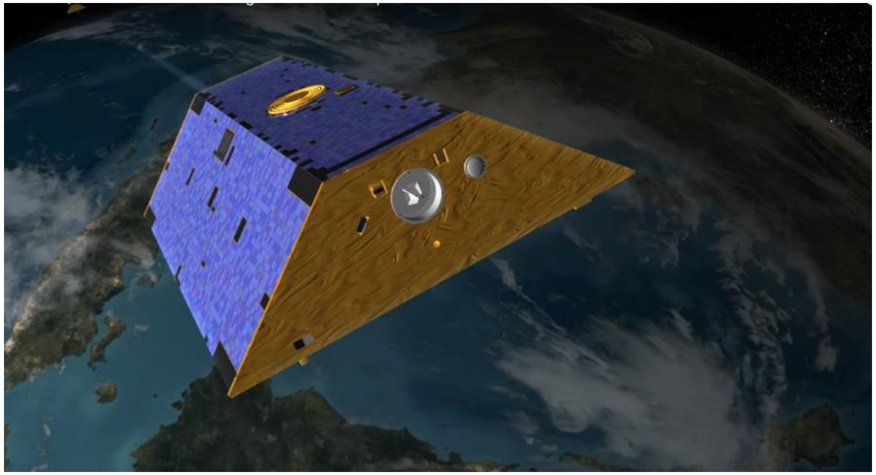
Slide from Josef Innerkofler

Processing tested: GRACE

- Gravity Recovery And Climate Experiment
- JPL Blackjack receiver
- Ultra Stable Oscillator
- Good attitude control
- Closed-loop tracking only

This satellite proved to be a good choice for algorithm testing and comparison between UCAR and the Wegener Center.

- Simple data format
- Use of nominal attitude
- Zero-difference processing



Processing details compared using UCAR codes

Time scales and clock corrections

Several different time scales are involved:

- GPS system time, equivalent to TT, Terrestrial Time (IAU 1991). This is the time scale we want to work in.
- LEO receiver time which includes receiver clock errors and relativistic effects. This is the time scale the measurements are in. Unlike for GPS, Bernese includes the periodic relativistic effect (perrel) in computing LEO clock offsets.
- GNSS transmitter time, which includes transmitter clock errors and relativistic effects. GPS clock offsets from IGS or CODE do not, by convention, include perrel.

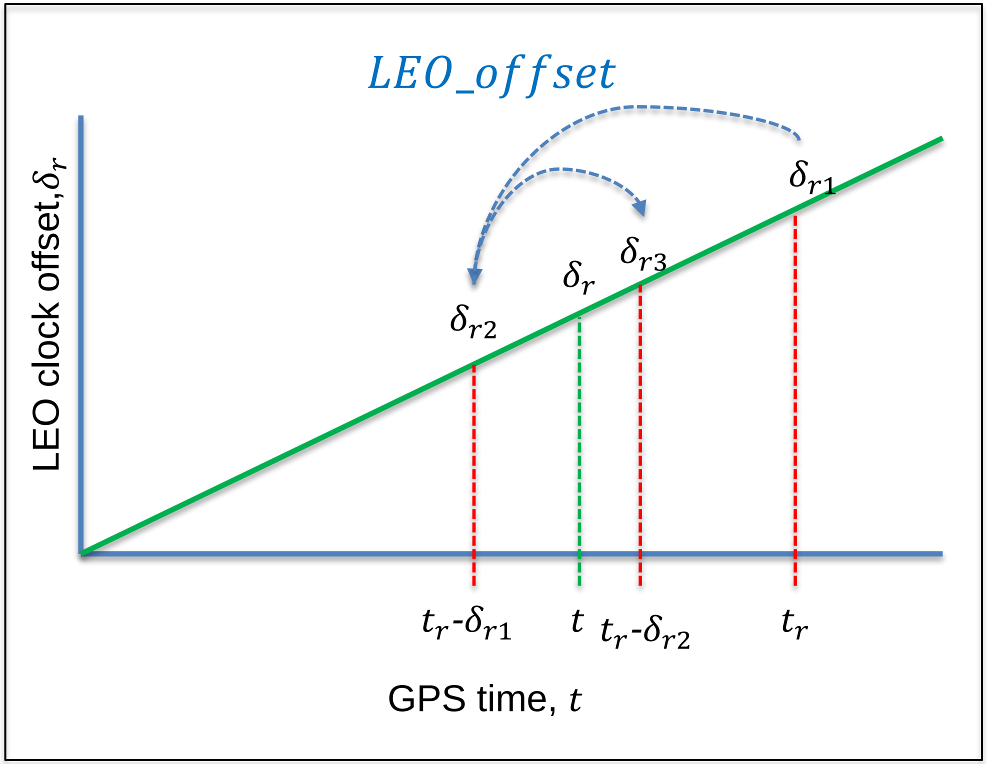
The first step after reading in high rate LEO data is to convert these data from LEO receiver time to GPS system time using the Bernese clock offsets. This is done so LEO positions can be looked up correctly.

Both LEO and GPS clocks are used in computing excess phase ($c\delta_r$ and $c\delta^t$ from the equation on a previous slide).

How to apply LEO clock corrections

LEO clock offsets from the POD subsystem are indexed in GPS system time, and contain clock offset values between GPS system time and LEO receiver time.

It is tempting to simply look up the LEO clock offset (δ_r) in the clock offset table using the receiver time (t_r), but this table is indexed in GPS time (t). If the receiver time offset is large and has a large slope (as is the case for GRACE), this can make a difference.



$t = t_r$

Loop until time does not change much:

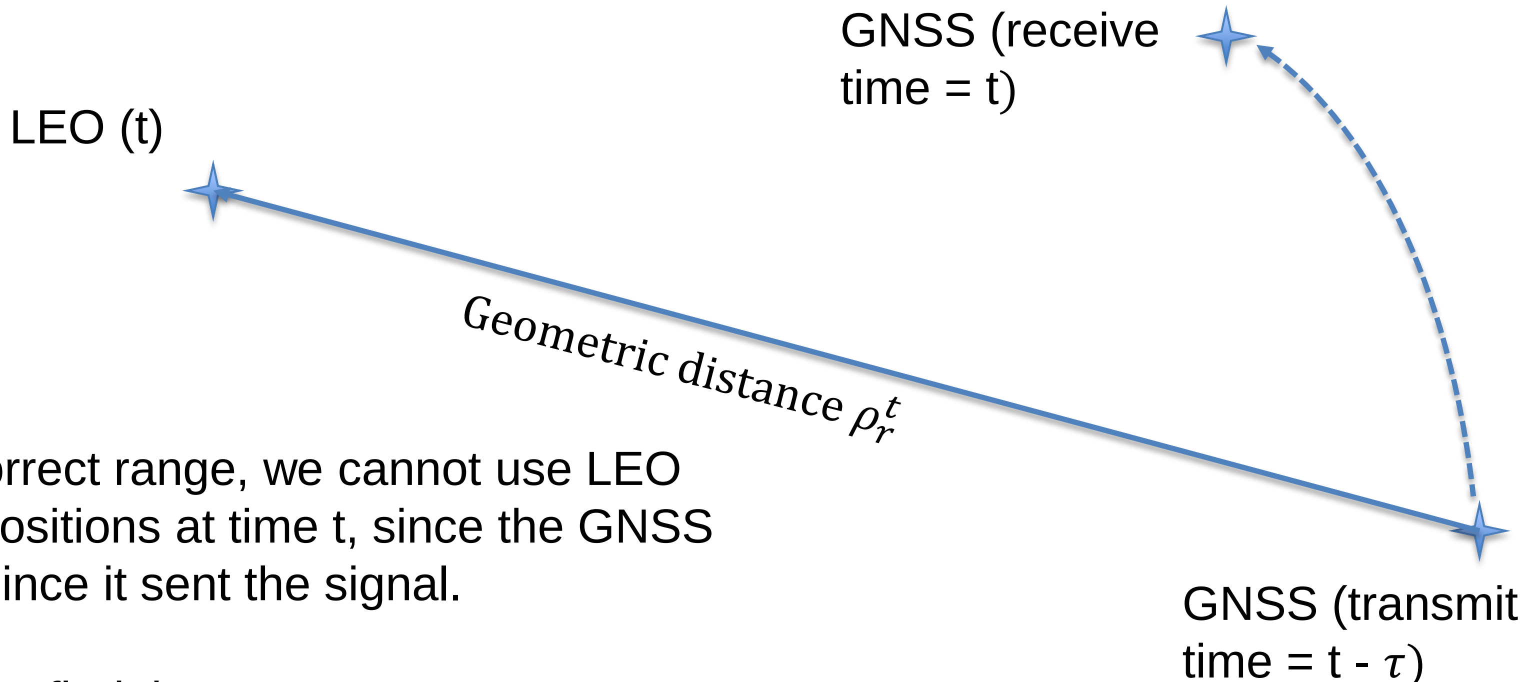
$\delta_r = LEO\_offset(t)$

$t = t_r - \delta_r$

$\delta_{r1}, \delta_{r2}, \delta_{r3}$ are progressively closer approximations to the correct value, δ_r

Thanks to Josef Innerkofler for this approach.

Finding correct range: GNSS at transmit time, LEO at receive time



To get the correct range, we cannot use LEO and GNSS positions at time t, since the GNSS has moved since it sent the signal.

Must iterate to find the correct range:

$\tau = 0$

Loop until range does not change much:

$$range = \sqrt{\sum[\vec{P}_{LEO}(t) - \vec{P}_{GNSS}(\mathrm{t}-\tau)]^2}$$

$$\tau = \frac{range}{c}$$

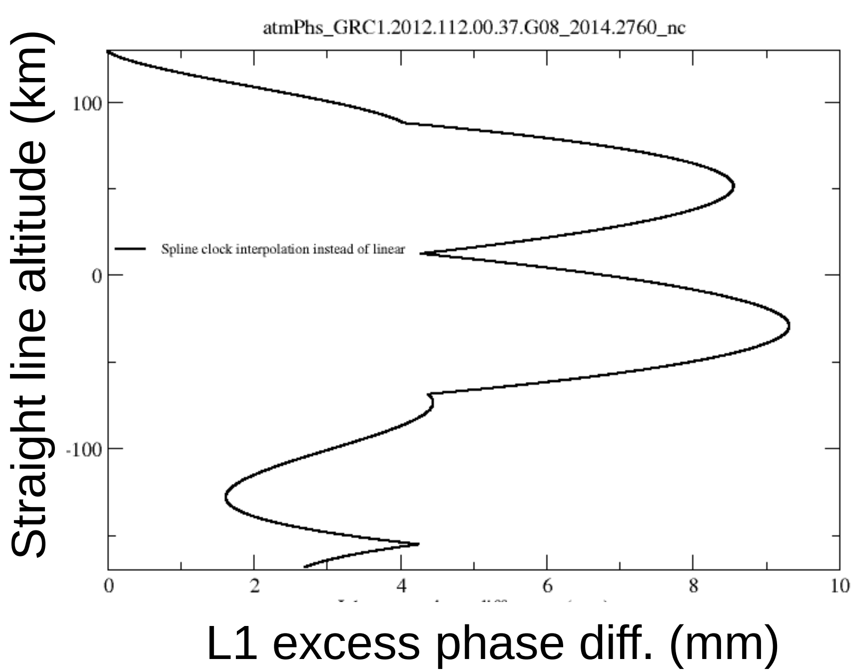
LEO clock correction interpolation method

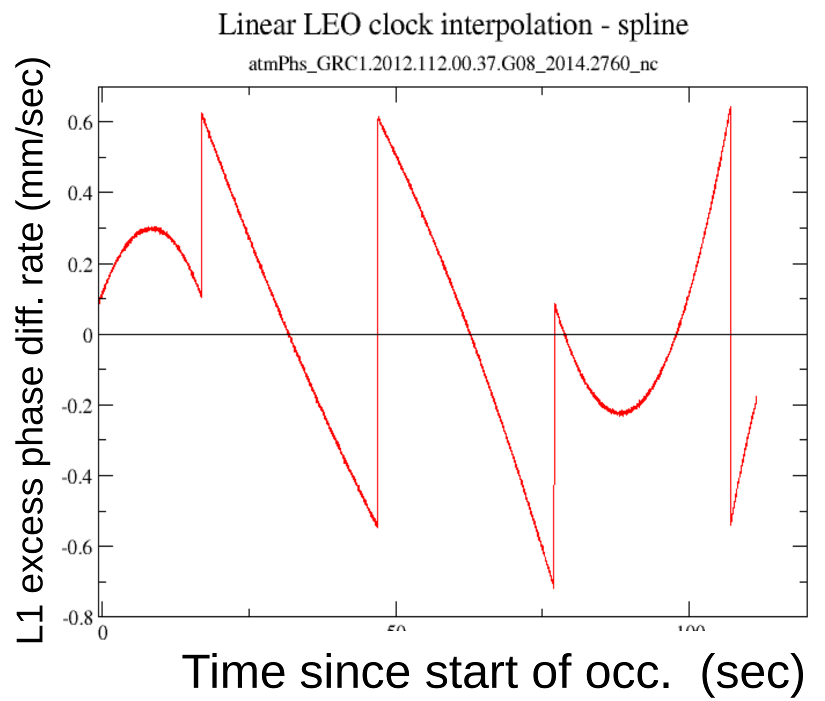
In order to get from the LEO clock offset times supplied by the POD subsystem (30-second values, typically) to the 50Hz receiver times, an interpolation method is necessary, which is applied during the loop described on the previous slide.

The choice of interpolation method is important. As shown in the left hand plot below, there is up to 10mm difference between using linear interpolation and cubic spline interpolation.

This translates into up to an 0.7mm/sec rate difference (right plot)

UCAR started out using spline interpolation for clock corrections, but switched to linear. I still don't know which is better.





Relativistic corrections

For GPS, Terrestrial Time is obtained from this equation:

$$TT = T_{raw} + \Delta T_{const} + \Delta T_{perrel} + \Delta T_{osc}$$

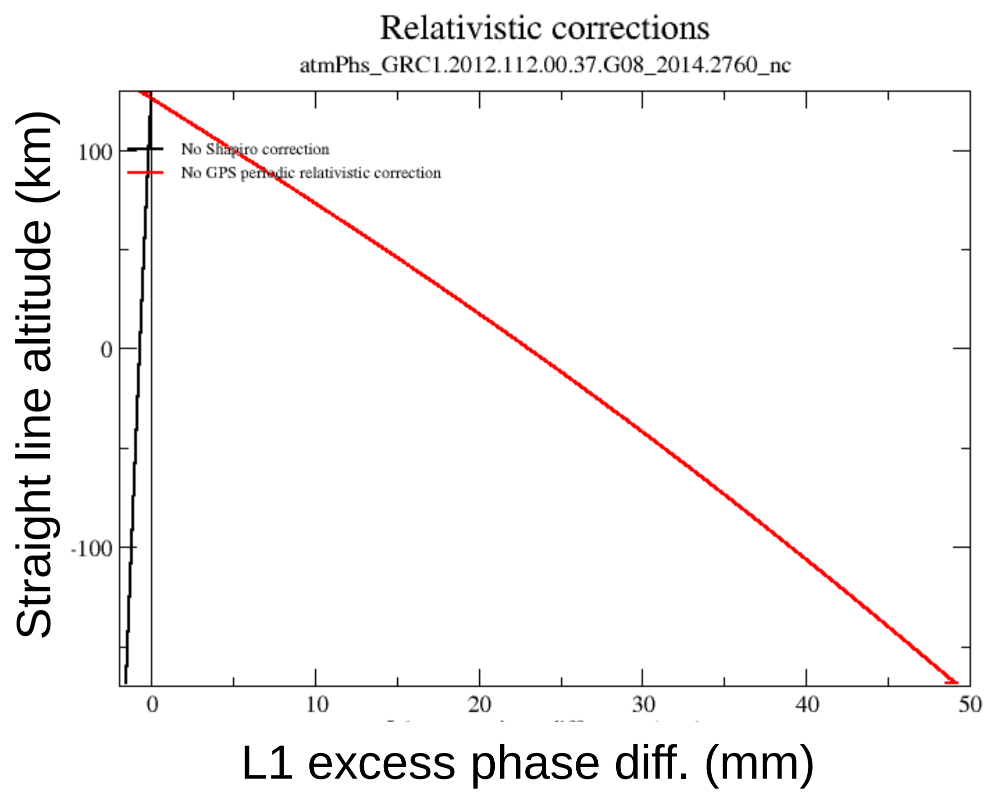
Where

- T_{raw} is the real clock time onboard the GPS satellite
- ΔT_{const} is a constant oscillator offset applied to all GPS, around 39 μsec per day.
- ΔT_{perrel} is the periodic relativistic correction, which, by IGS convention, is not applied to GPS clock solutions [Kouba, 2004]
- ΔT_{osc} is the GPS oscillator error, which is solved for in the clock solution

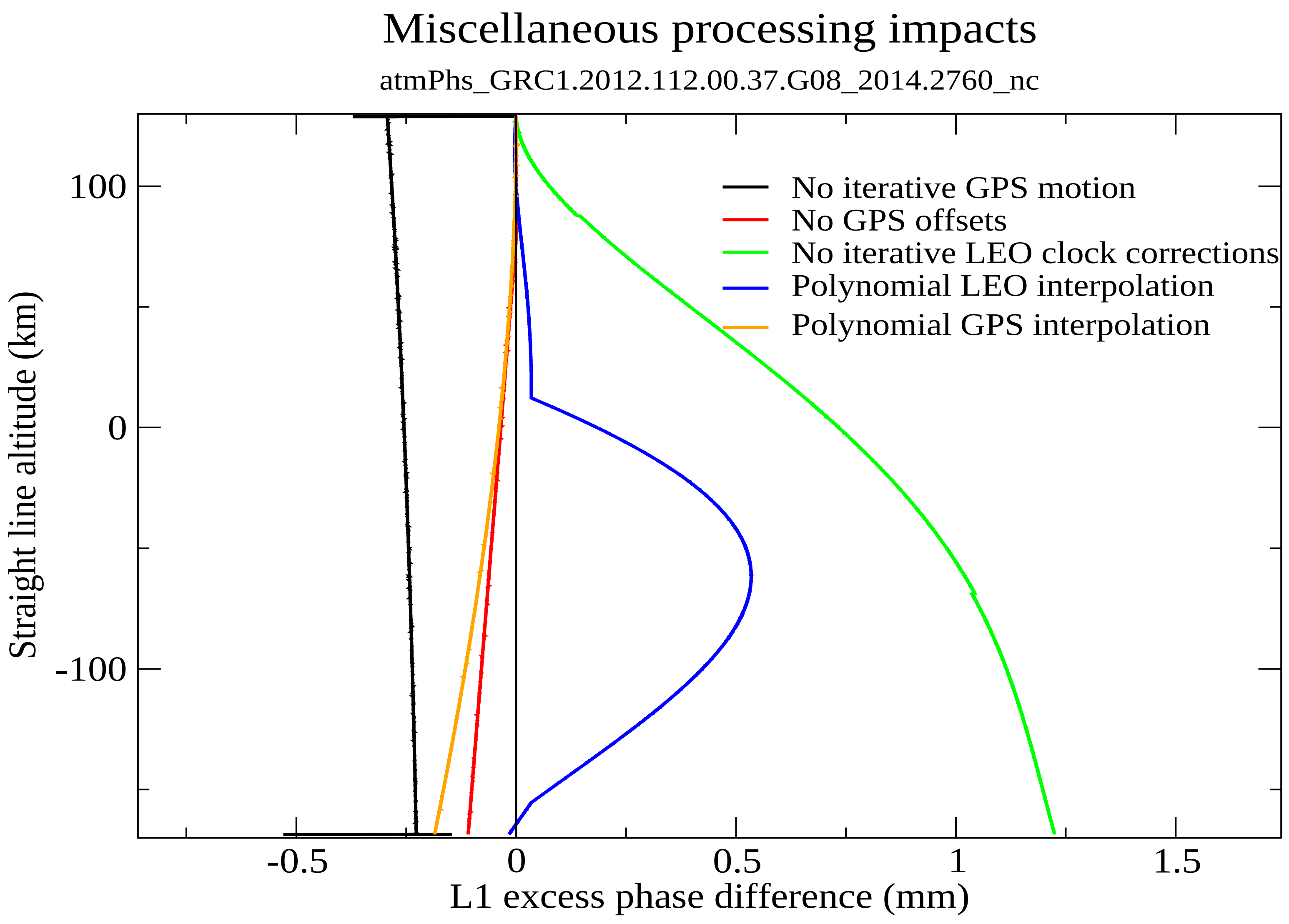
Failing to apply this correction to GPS clocks in the excess phase code has the effect shown in the red curve on the right:

The smaller Shapiro effect (black curve on the right) also needs to be applied [Ashby, 2003]. This correction depends on the path taken by the ray and is thus applied to the range directly:

$$\Delta r_{shapiro} = \frac{2GM_E}{c^2} ln \left[\frac{r_{gps} + r_{leo} + d}{r_{gps} + r_{leo} - d} \right]$$



Other processing impacts

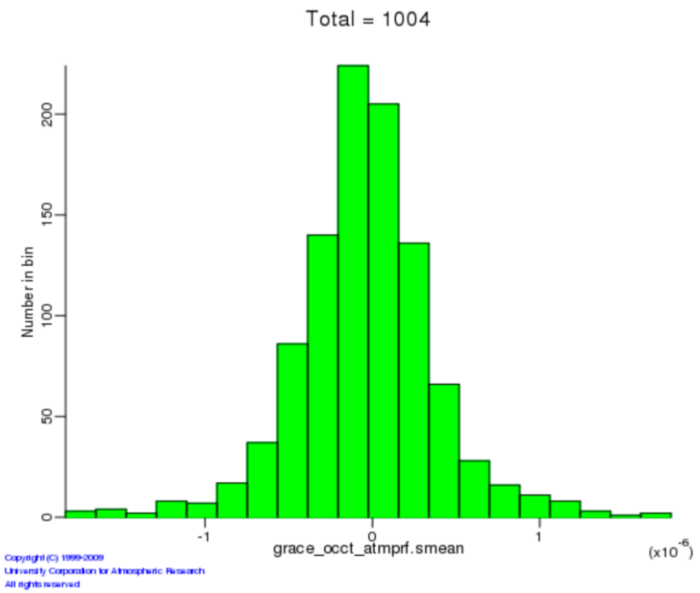


Summary of processing effects

Name of effect	mm/sec	μrad
LEO attitude and phase center corrections	0.83	0.332
Linear LEO clock interpolation vs. spline	0.7	0.26
GPS periodic relativistic correction	0.446	0.178
Shapiro correction	0.0134	0.0054
Iterative LEO clock correction	0.0107	0.0043
Polynomial LEO orbit interpolation (vs. trigonometric)	0.0045	0.0018
Iterative GPS motion correction	0.0027	0.0011
Polynomial GPS orbit interpolation (vs. trigonometric)	0.0018	0.00072
GPS attitude and phase center corrections	0.0011	0.00044

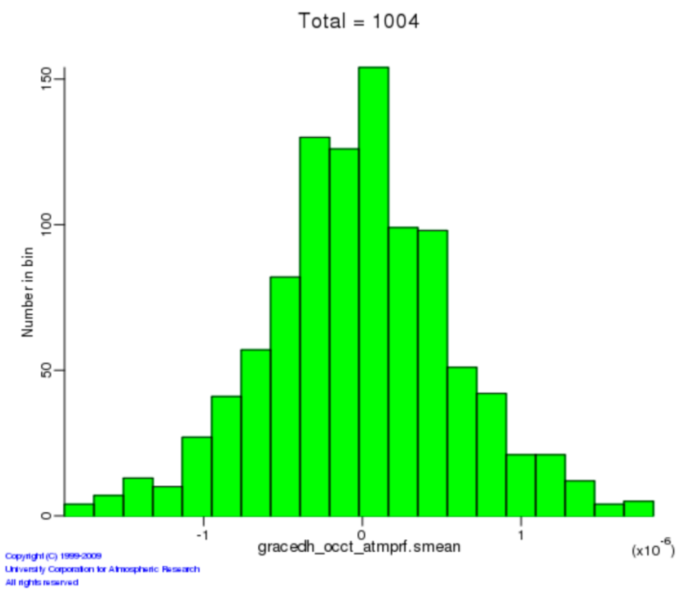
What level of effect is detectable in higher level products?

Perrel included



STD DEV = 0.418 μrad

Perrel omitted



STD DEV = 0.595 μrad

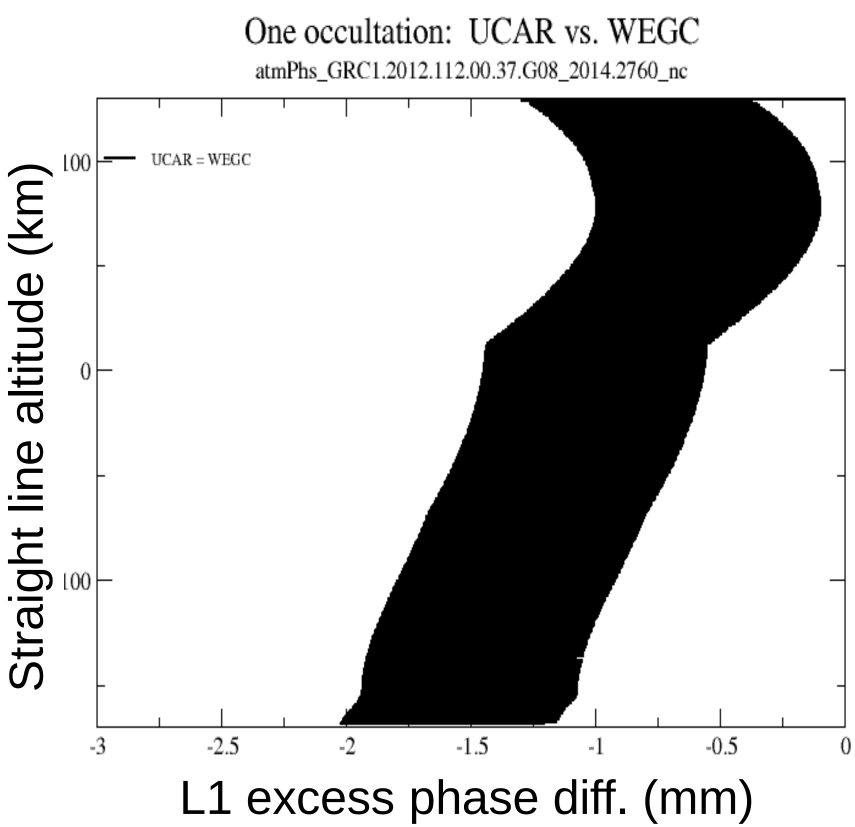
Many effects from the previous table are too small to detect in bending angle statistics. The larger ones are noticeable, however.

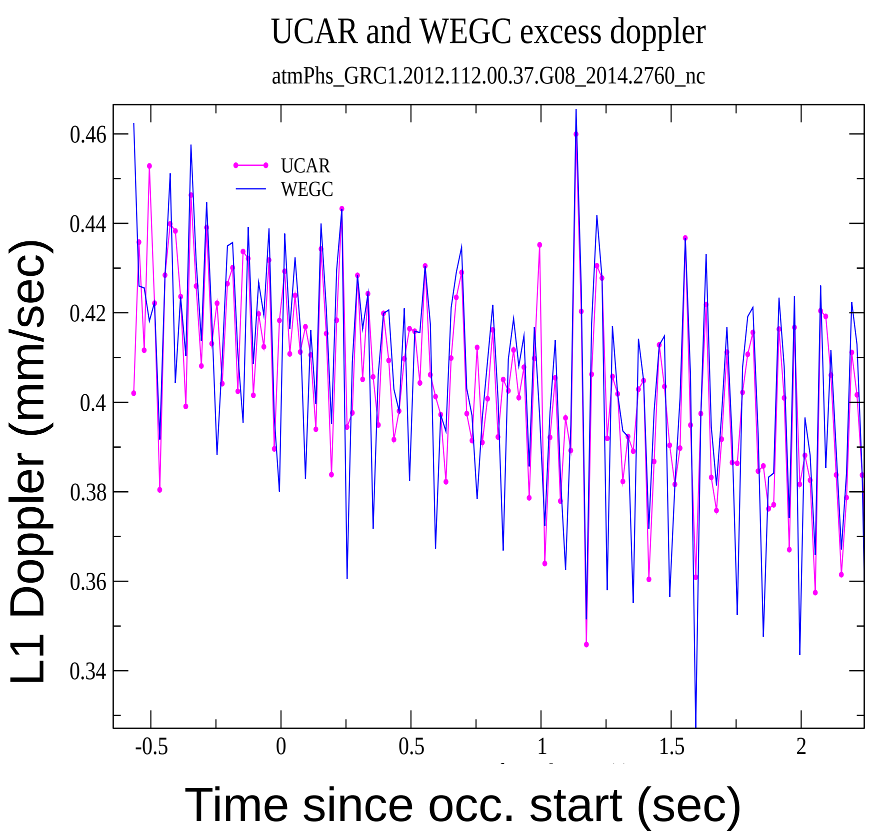
The periodic relativistic effect is taken into account correctly in the above left plot, whereas it is neglected in the above right plot. The spread of 60-80km bending angle noise is noticeably larger in the above right plot, as shown in the standard deviation values.

Comparison of UCAR and Wegener Center codes

Single occultation

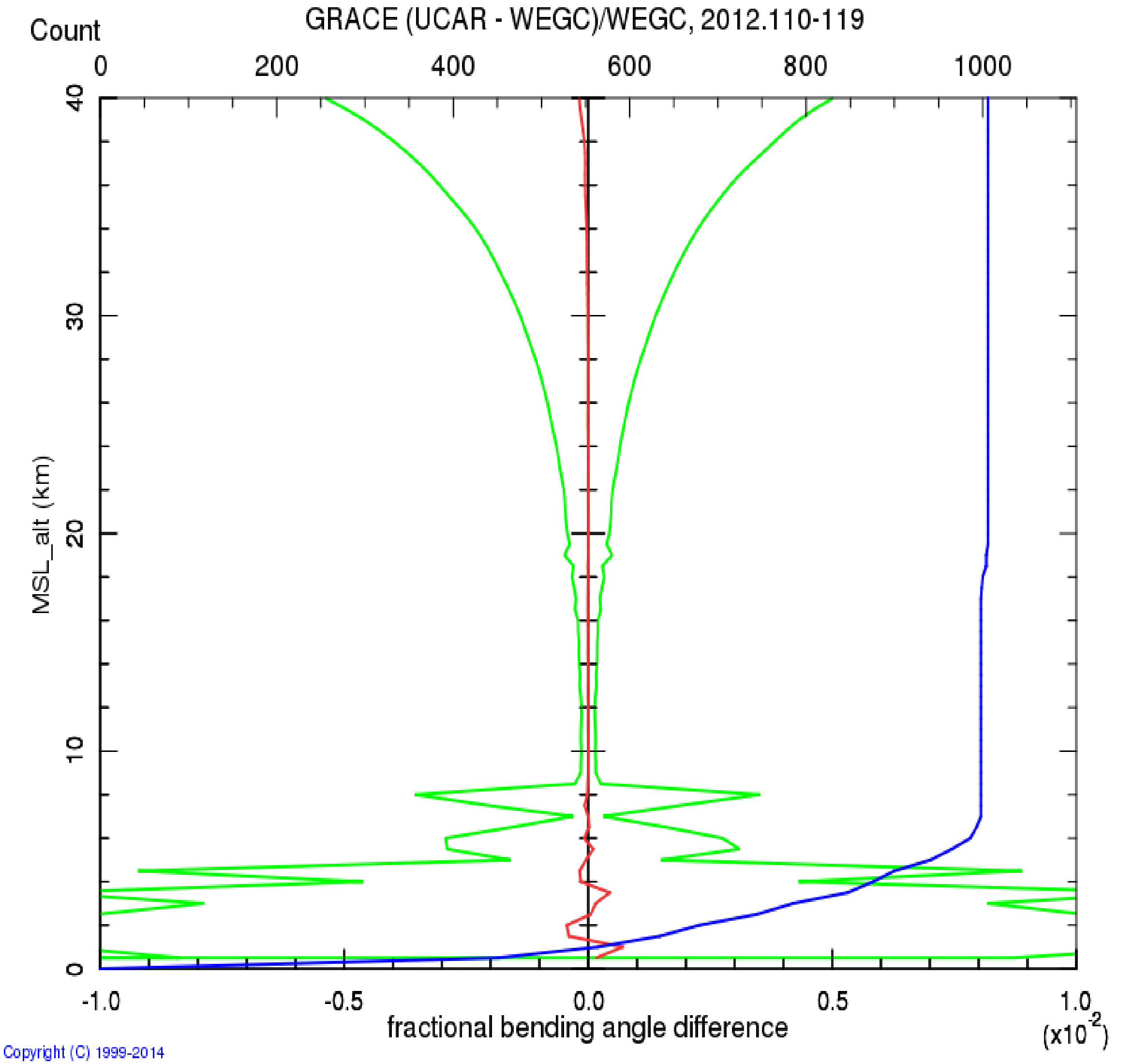
- The same occultation is used as for the processing effects comparisons on previous slides
- The spreading of the difference line indicates high frequency jitter on both UCAR and WEGC excess phases at the mm level
- This looks to be a combination of thermal noise, ionospheric effect, and numerical precision issues





Statistics

- Ten days worth of processing, 2012.110-119
- $\frac{UCAR-WEGC}{WEGC}$ statistics by altitude for almost 1000 occultations
- Using the same orbits and clock corrections
- Result of cooperative effort in understanding and reducing the effects of:
  - Clock interpolation
  - Time scales
  - Inertial reference frames
  - Relativity correction
  - Phase center offsets
  - Orbit interpolation
- Does not include GPS phase center offsets (a small effect)



Conclusion

- A six month visit from WEGC was spent at UCAR in comparing and perfecting excess phase processing strategies
- The focus was on zero-difference processing of the GRACE mission
- Correct processing includes careful attention to many details, including:
  - Time scales and clock correction
  - Relativistic corrections
  - Orbit interpolation
  - Satellite attitudes and phase center offsets for both transmitter and receiver
- Effects above a certain magnitude in excess phase/Doppler are visible in bending angle retrieval statistics
- Many improvements and bugs were found in code from both centers
- Thanks to Josef for a productive visit!

References

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Backup slides

Excess Doppler $\rightarrow$ bending angle

$$\Delta D(t) \rightarrow \boxed{\begin{gathered} \Delta D + \dot{R}_{\mathrm{LG}} - \left(|\dot{\bar{R}}_{\mathrm{L}}| \cos\varphi(a) - |\dot{\bar{R}}_{\mathrm{G}}| \cos\chi(a) \right) = 0 \\ \varphi(a) = \zeta - \arcsin\left(\frac{a}{|\bar{R}_{\mathrm{L}}|}\right) \\ \chi(a) = (\pi - \eta) - \arcsin\left(\frac{a}{|\bar{R}_{\mathrm{G}}|}\right) \\ \alpha = \Theta - \arccos\left(\frac{a}{|\bar{R}_{\mathrm{L}}|}\right) - \arccos\left(\frac{a}{|\bar{R}_{\mathrm{G}}|}\right) \end{gathered}} \rightarrow \alpha(a)$$

(e.g., Melbourne et al. 1994)

- Bending angle derived from Doppler is used in the stratosphere and perhaps upper troposphere, but not in the lower troposphere
- In the moist lower troposphere, multipath propagation may be present, and more advanced methods has to be used to derive the bending angle

Why compute excess phase at all?

It is possible to invert full phase instead of excess phase.

Why do we use excess phase as an auxiliary observable instead of the full phase + orbits?

Here are some considerations:

1. On the reference link (if we are single differencing), calculation of excess phase is fundamentally needed to isolate clocks from GPS-LEO motion and use it for correction of the occulted link.
2. On the the occulted link, calculation of excess phase is not needed—full phase can be inverted. The full phase still needs to be corrected for clock and relativistic effects however.
3. Excess phase is, however, convenient for quick assessments – it represents the effect of the atmosphere on the RO signal. But only approximately: Excess phase is not fully independent on the GPS and LEO positions.
4. Wave optics inversion uses full phase (by adding excess phase back to GPS-LEO distance).
5. Geometric optics inversion can use full phase or excess phase.
   a) Inversion of full phase needs accurate orbits (velocity error 1 cm/s => BA error 5 μrad)
   b) Inversion of the excess phase needs accurate orbits for only calculation of excess phase.
   After that, orbit accuracy can be degraded (velocity error 1 cm/s => negligible BA error).
   Excess phase is represented by a smaller number than full phase.
6. Computing excess phase does have several other advantages:
   a) Consolidation of processing flow. Excess phase processing acts as a multiplexer, combining many complex inputs into one excess phase file.
   b) Standardization between processing centers. The CDAAC **atmPhs** format has become a de-facto standard in the RO processing community for exchange and comparison of data.
   c) Preservation of numerical precision. There is a tendency to run out of precision if full phases are used instead of excess phases.
   d) Tradition! UCAR and other centers have been processing this way since GPS/MET in the 1990's.

<u>Summary</u>: (1), (3), (5b), and (6) support the use of the excess phase as an auxiliary observable instead of full phase. Motion carried!

Orbit interpolation method is important

LEO and GNSS orbits are supplied in tabular SP3 format files. These files have low resolution, typically 1-minute for LEO orbits and 15 minutes for GNSS orbits.

Below are two views of the same plot, one full-scale, one zoomed in. The plots compare 1-minute orbits interpolated to 50Hz with 1-second orbits (called ‘truth’ in the plot) also interpolated to 50Hz.

The red line shows cubic spline interpolation, the green line shows the interpolation used at UCAR which is based on a trigonometric series, optimized for interpolating inertial orbits [Schenewerk, 2003]. In this case, spline interpolation can be 10’s of meters off, but trigonometric interpolation only ~5 cm off.