Carrier Phase Multipath Characterization and Frequency Domain Bounding

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Position estimation from GNSS readings

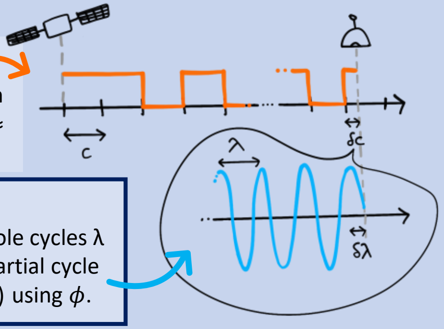
- Range measurements from 4 or more GNSS satellites are required to estimate user position and time
- 2 ways to compute range:

Code

Count whole chips c between satellite and antenna, error δc < c ≈ 300m (limited precision).

Carrier phase (ϕ)

Estimate (ambiguous) number of whole cycles λ between satellite and antenna and partial cycle δλ known precisely (centimeter-level) using ϕ.



Carrier phase model

k – time | f – frequency | s – satellite | r – receiver

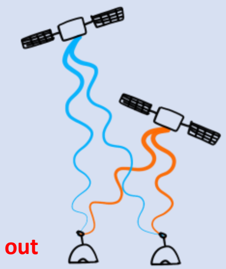
$$\phi^{k(f)}_{s(r)} = \underbrace{\rho^{k}_{s(r)}}_{\text{range}} - \overbrace{I^{k(f)}_{s(r)}}^{\text{ionospheric delay}} + \underbrace{T^{k}_{s(r)}}_{\text{tropospheric delay}} + \overbrace{c(\delta t^{k}_{(r)} - \delta t^{k}_{s})}^{\text{clock biases}} + \underbrace{\lambda^{(f)} n^{k(f)}_{(r)}}_{\text{cycle ambiguity}} + \overbrace{v^{k(f)}_{s(r)}}^{\text{multipath}} \quad [\text{m}]$$

Carrier phase multipath characterization

Dual Antenna (DA)

Subtracting same frequency ϕ measurements from 2 satellites and 2 antennas

→ Isolates multipath and cycle ambiguity



MP cancels out

Dual Frequency (DF)

Subtracting distinct frequencies ϕ measurements from 1 satellite and 1 antenna

→ Isolates multipath, cycle ambiguity and ionospheric delay

Ionospheric delay mitigation

Ionospheric delay seems to be a phenomenon with natural frequencies substantially lower than that of multipath.

→ High pass filtering to separate multipath from ionospheric delay

Cutoff frequency computation

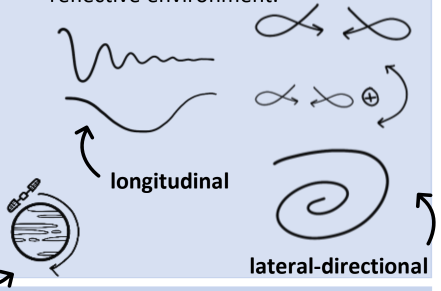
1. Run International Reference Ionosphere (IRI) custom simulation to get slant ionospheric delay over 1 sidereal day at a specific location on Earth
2. Replicate slant ionospheric delay over 7 sidereal days
3. Estimate frequency content using Lomb-Scargle Power Spectral Density (PSD)
4. Compute filter cutoff frequency using 40dB drop from maximum peak (magnitude divided by 100 in the time domain)

Cutoff frequency validation

A cutoff frequency validation function is derived from a simple multipath geometric model, whose parameters are the rate of change of the reflective environment, as well as horizontal and vertical distances of the GNSS antenna to the closest surfaces most likely to generate multipath.

An antenna in a static environment is only affected by satellite dynamics.

An airborne airplane, however, has dynamic modes that affect the reflective environment.

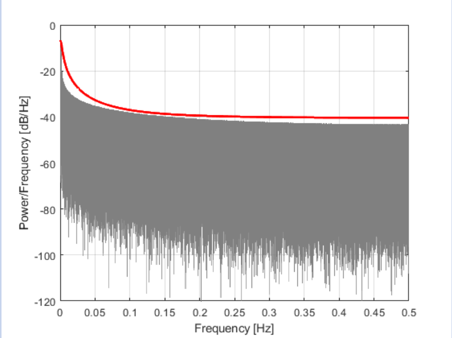


Frequency domain bounding

From the high pass filtered carrier phase measurements:

1. Map the data sequences with a deterministic function to force stationarity
2. Split the data sequences into locally stationary sub-sequences with an adaptative windowing algorithm, ditch the sub-sequences that are still deemed non stationary
3. Take the PSD of each thus generated stationary sequence
4. Upper bound every sequence with a Gauss-Markov Random Process (GMRP) + White Noise (WN) model

Rooftop benchmark case results



The **GMRP+WN** model upper-bounds all **DF carrier phase multipath PSD** with a chosen security factor (min. PSD to model distance > σ at all frequencies) with parameters:

$$\begin{cases} \sigma_{GMRP} = 4.6 \text{ cm} \\ \tau_{GMRP} = 45 \text{ s} \\ \sigma_{WN} = 0.9 \text{ cm} \end{cases}$$

→ Expected $\sigma_{GMRP} + \sigma_{WN} \approx$ 1 cm

Conclusion

- Developed DF multipath characterization
- Investigated feasibility of ionospheric delay removal by high pass filtering DF single differenced carrier phase measurements
- Chose PSD upper bound model for DF carrier phase multipath
- Investigated theoretical feasibility of DF characterization method for aircraft

Applications

→ When upper-bounding errors over time is preferred over a snapshot model

Kalman **F**ilter-based applications:

- Robust sensor fusion
- **A**dvanced **R**eceiver **A**utonomous **I**ntegrity **M**onitoring (ARAIM)

Future work

- Validate ionospheric delay removal method on real ionospheric data
- Design an absolute cutoff frequency computation method (*c.f. Cutoff frequency computation 4.*)
- Validate DF method with different frequency combinations (any GNSS)
- Investigate filters, PSD algorithms and upper bound optimization
- Study link between DF carrier phase multipath and *iono-free* combinations used in ARAIM

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