Cycle Ambiguity Resolution

in GNSS-R Carrier Phase Altimetry

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Introduction

- Coherent reflections have been collected from space over sea ice and ocean (at grazing geometry as that for RO):

  → **CHAMP, UK-DMC, TDS-1, CyGNSS …**

- ESA has recently studied, assessed or approved GNSS Reflectometry mission concepts based partly or fully on carrier phase observables for altimetry applications:

  → **GEROS-ISS** on board the International Space Station
  → **G-TERN** Earth Explorer 9 proposal
  → **FSSCat** cubesat mission (approved)
  → **SaaS Pioneer** cubesat mission (approved)
  → **PRETTY** cubesat mission (approved)

- This presentation addresses the issue of carrier phase ambiguity resolution

Carrier Phase Ambiguity

- Carrier phase observable

$$\lambda l = r + a - e + \lambda W_S - \lambda n$$

λ wavelength

l measured relative phase (cycles)

r relative distance

a relative tropospheric path excess

e relative ionospheric phase path advance

W_S wind-up due to reflection at specular point S (cycles)

n relative integer ambiguity (cycles)

Carrier Phase Ambiguity

- Carrier phase observable (interferometric processing)

$$\lambda l = r + a - e + \lambda W_S - \lambda n$$

- The quantity of interest is ***r***

- To find ***r*** it is necessary:

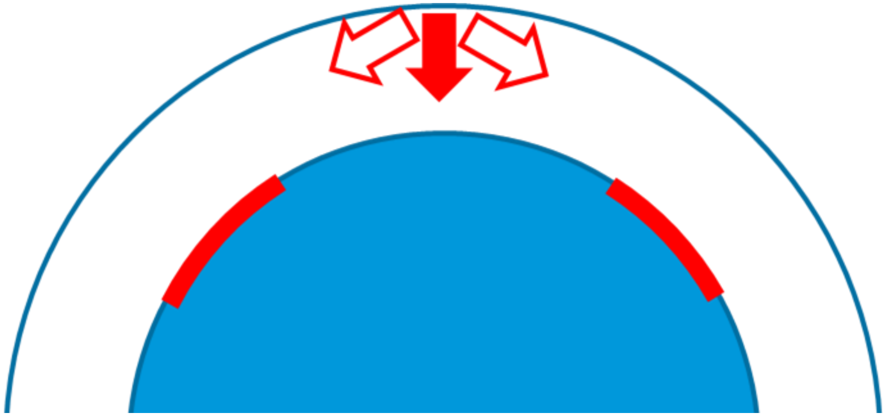
  $\rightarrow$ to estimate ***a***, ***e*** and *(λ **Ws**)* to well less than *λ*
  $\rightarrow$ then to solve for the integer ambiguity ***n***

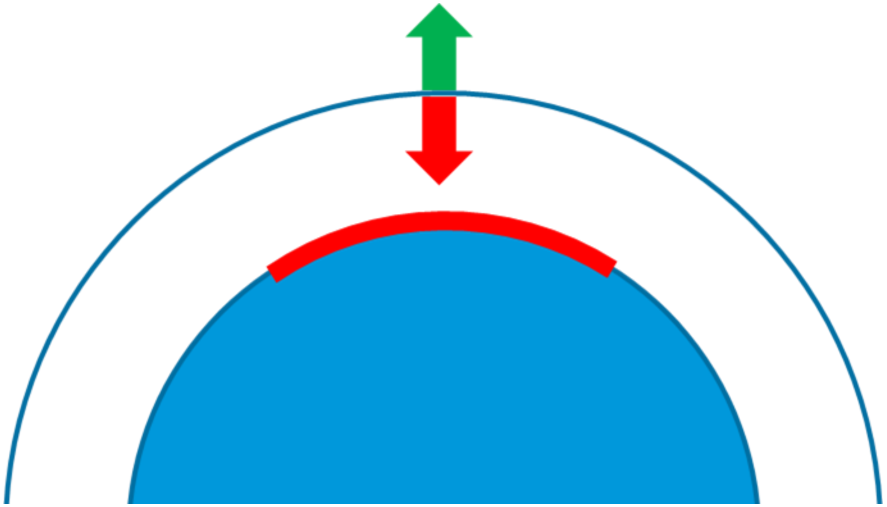
- Requisite: position of receiver and GNSS transmitter known to better than *λ* (only relative vector projected errors matter)

Considerations on Geometry

GRAZING

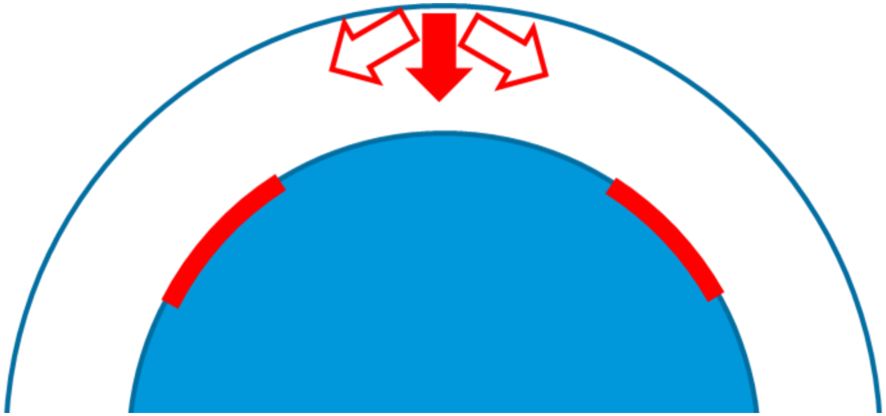
AROUND NADIR





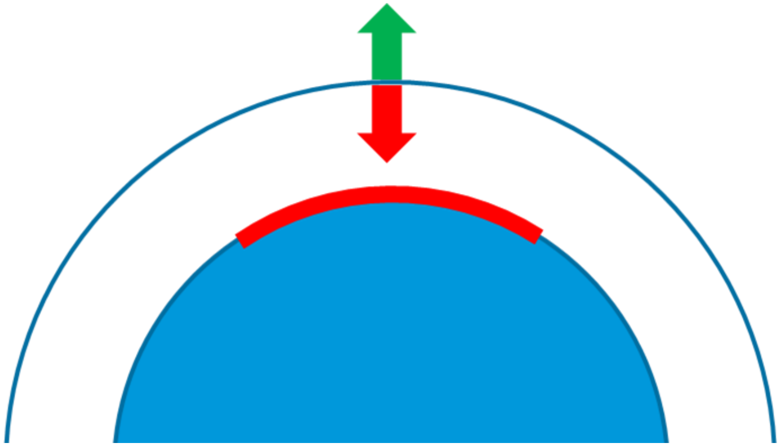
Grazing Geometry

- Observable targets: **all surfaces** (Rayleigh criterion)
- Polarization of reflected signal: mixed LHCP**/RHCP**
- **Low integer ambiguity** induced by geometry
- **Small** direct-to-reflected signal **angular separation** $\rightarrow$ **same antenna**
- Integer ambiguity **very insensitive** to **instrumental errors**
- **More** pronounced atmospheric effects (larger ***a*** and ***e***)
- Integer ambiguity **very insensitive** to **satellite position errors**



Around-Nadir Geometry

- Observable targets: **very calm ocean**, **in-land water**, **sea ice**
- Polarization of reflected signal: **LHCP**
- **Large integer ambiguity** in the number of carrier cycles
- **Large** direct-to-reflected signal **angular separation** $\rightarrow$ **2 antennas**
- Integer ambiguity **sensitive** to **instrumental errors**
- **Lower** atmospheric effects (smaller ***a*** and ***e***)
- Integer ambiguity **sensitive** to **receiver satellite radial error**



Tropospheric Excess Path Estimation

- Importantly impacts grazing observations (longer traversed path)
- Dry excess path can be estimated within λ using models
- The variable wet troposphere is problematic for grazing geometry
- Possible way around: solve integer ambiguity at different segments of the entire reflection arc and retain that with lowest residuals

Ionospheric Phase Path

- Affects mostly grazing geometry (longer traversed path)
- The ionospheric phase path advance can be found with dual frequency observations
- Integer ambiguity to be fixed in the part of the arc with lowest TEC
- Trade-off between use of widelane or use of 3 frequencies

Satellite Position Errors

- Position uncertainty of GNSS transmitter not critical as it projects the same along direct and reflected path
- Position uncertainty of GNSS-R satellite not critical either in grazing geometry
- Radial component of position uncertainty of GNSS-R satellite is important in around-nadir geometry
- Position uncertainty of GNSS and GNSS-R can be known to a few centimeters in post-processing – thus, not a critical error source
- Note: GNSS-R must carry a dual-frequency POD GNSS receiver

Importance of instrument architecture and processing approach

- Instrument architecture is critically important for the ambiguity resolution, in particular for around-nadir geometry

- Processing approach is fundamental to the quality of the carrier phase observables, both single frequency and widelaning

Integer Ambiguity Resolution

- Many methods exist
- These methods can accommodate widelane and multi-frequency
- Example: the Null Space Method (used in ESA’s PROBA-3 mission) uses very few epochs to arrive to a solution
- The Null Space Method is robust against re-initialization (when phase track is only intermittently tracked, or when tracked only for a very short period of time)

Conclusions and Way Forward

- Considerations have been given on ambiguity resolution
- In principle it should be possible to solve for it and retrieve absolute heights from carrier phase GNSS-R altimetry
- A ground-based experiment is proposed for demonstration