EXPLORING GROUND BASED AND AIRBORNE CARRIER PHASE GNSS-R ALTIMETRY

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OUTLINE

- Receiver processing description
- Measurement results
  - 60 meter lighthouse
  - Lake from ground level
  - Sea from 350m cliff
  - Lake from 600m aircraft
- Carrier phase Ambiguity resolution
  - Issues with local geoid
  - Issues with tropospheric delay
- Possible novel applications of GNSS-R

Published in « Reflectometry with an open source SW GNSS receiver: Use case with carrier phase altimetry », IEEE JSTARS, oct 2016
The GNSSR-MP (or SNR or IPT) method is an indirect way of making Differential Carrier Phase (DCP) measurement between the direct & reflected signal.

Therefore if the SNR method works, then Carrier Phase GNSSR can work even better if we find the appropriate signal processing.
GNSS REFLECTOMETRY INSTRUMENT (CNES/GET/GRGS)

Instrument architecture:
- differed time processing

- « Bit grabber »
  ADC & recording

- Post processing software
  • « Echo L-P » (Syntony lab)
  • « GLORI » instrument (CESBIO)
  • « SDR Lite » (Ingespace)

- Modified GNSS-SDR
SIGNAL PROCESSING ALGORITHM:
SLAVED REFLECTED ANTENNA + ENHANCED COHERENT INTEGRATION TIME

Diagram showing the processing flow with boxes for various stages such as direct signal, reflected signal, correlators, NCOs, and processing blocks like carrier discriminator & filters, code discriminator & filters, data bit sign, and open loop processing.
ENHANCED SIGNAL PROCESSING : BENEFITS

- Robustness: Reflected signal is slaved on the direct signal
- Data wipe-off: Coherent integration time can be increased well beyond the usual 20 ms limit.
- Amplitude & Carrier phase difference can be directly measured from the filtered correlator outputs

\[
\Delta \phi_{R-D}(t) = \text{unwrap} \left( \arctan2(Q, I) \right)
\]

USE OF GNSS-SDR

- GNSS-SDR: open-source GNSS SW receiver from CTTC (Centre Tecnologic de Telecomunicacions de Catalunya)
- Benefit: GNSS signal acquisition, tracking, channel management, data demodulation for the direct antenna are re-used « as is ».
- « grafting » of the reflected antenna signal processing
- Initialy developped with version 0.0.5, now migrated to version 0.0.8 (released may 2016)
- Execution speed depends on:
  - Number of satellites
  - Number of correlators
  - RF sampling rate
  - Computer used
  - Whether there is a channel in acquisition
RESULTS AT CORDOUANS LIGHTHOUSE (H=60M)

Signals recorded with « Echo LP » data recorder lend by Syntony
30 second recording made on mai 31, 2013, at low tide.
Tilted antenna setup
Impact of long coherent integration time:

Raw correlator output (Tint = 1 ms)

After 500 ms CIT, plus Hamming window filtering:
CARRIER PHASE UNWRAPPING : EXAMPLE FOR PRN 15

Modelled elongation according to satellite motion (from SP3 files)
Measurement precision : 1 cm, but 19.03 cm integer ambiguity
RESULT WITH MULTI CORRELATOR PROCESSING

PRN25, 27° elevation satellite, $\rightarrow$ C/No oscillation on the direct signal
RESULT FOR PATH ELONGATION: EVERY SATELLITE IN VIEW

« cycle slip »

65° & 78° elevation → ground reflection (partly ?)

Cycle slip

5° elevation
Very low elevation satellite (5°) + Antenna tilted at 20° = Direct signal leakage on the reflected antenna (vice-versa)
LAKE AT GROUND LEVEL (H~2M)

Carrier Phase Difference measurements. Measurement noise < 0.01 carrier cycle → Millimeter accuracy possible
350 METER HIGH COASTAL CLIFF AT LA CIOTAT

Rough sea (SWH between 0.5 and 1 meter) on the observation day. No satisfactory results yet (too many cycle slips)
SAFIRE ATR42 FLIGHT RESULTS

Opportunity flight over Biscarrosse lake during a GLORI recording session

600 m high overfly, at 95 m/s speed

Night flight, calm wind

36 second recording.

Reflections from 9 GPS satellites where measured. (8 simultaneously)

Aircraft trajectory reconstructed from direct antenna measurements using RTKLIB and L1 data from « mimz » reference station. Aircraft attitude recorded
600-METER ATR42 FLIGHT RESULTS – AN EXAMPLE

IQ diagram, PRN 32
Green: direct, blue: reflected

Reflected-Direct CPD
Red: measured, blue: modelled

Model: path elongation due to satellite and aircraft motion
PRN32 is at 23° elevation and descending
600-METER ATR42 FLIGHT – MORE RESULTS

9 satellites reflections observed (8 simultaneous), 4 more examples:

- PRN10, elevation 12°
- PRN32, elevation 23°
- PRN17, elevation 46°
- PRN3, elevation 66°
600-METER ATR42 FLIGHT – MORE RESULTS

9 satellites reflections observed (8 simultaneous), 4 more examples:

- **PRN6**, elevation °
- **PRN9**, elevation 41°
- **PRN**, elevation °
Observation of a growing range error highly correlated with signal Doppler

\[ \varphi_r(t + \delta t) - \varphi_d(t) = \varphi_{r-d}(t) + \text{Doppler} \times \delta t \]

→ Désynchronisation \( \delta t \) between direct & reflected sampling epoch due to different OL used (GLORI built for measuring amplitude, not carrier phase)
Basic modelisation:
- Plane reflecting surface
- N reflection points, N equations:

\[ \Delta L_{R-D,i} \cdot \lambda = 2h \sin \varepsilon_i + N_i \cdot \lambda + b \]

- Single difference to remove common bias \( b \) \( \rightarrow \) N-1 equations:

\[ \Delta ij L_{R-D} \cdot \lambda = 2h \Delta ij \sin \varepsilon + \Delta ij N \cdot \lambda \]

Integer ambiguity search to solve for \( h \).

Too simple!
CORRECTION FOR EARTH SHAPE : ELLIPSOID

Correction according to elevation:

Correction magnitude @ El=10°:

<table>
<thead>
<tr>
<th>Height</th>
<th>Elevation</th>
<th>Azimuth</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m</td>
<td>0.01 cm</td>
<td>~0</td>
</tr>
<tr>
<td>100 m</td>
<td>1 cm</td>
<td>0.01 cm</td>
</tr>
<tr>
<td>600 m</td>
<td>34 cm</td>
<td>0.1 cm</td>
</tr>
<tr>
<td>2000 m</td>
<td>378 cm</td>
<td>1.2 cm</td>
</tr>
</tbody>
</table>

Correction : δellip(\(\hat{h}\), Az, ε)

\(\hat{h}\): modelled height
CORRECTION FOR EARTH SHAPE : GEOID SLOPE

Geoid height vs WGS84 ellipsoid in France
(equidistance = 1 meter)

Geoid model at biscarrosse lake:
\[ \gamma = 1.8 \text{ cm/km} \]
\[ A_{z_{\text{geoid}}} = 30^\circ \]
\[ \gamma_N = \gamma \cos A_{z_{\text{geoid}}} \]
\[ \gamma_E = \gamma \sin A_{z_{\text{geoid}}} \]

Correction:
\[ \delta_{\text{geoid}}(\hat{h}, A_z, \varepsilon, \gamma_N, \gamma_E) = 2\hat{h} \cos(\varepsilon) \times (\gamma_N \cos(A_z) + \gamma_E \sin(A_z)) \]

Magnitude:

<table>
<thead>
<tr>
<th>Height</th>
<th>Correction max</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 m</td>
<td>0.4 cm</td>
</tr>
<tr>
<td>600 m</td>
<td>2.2 cm</td>
</tr>
<tr>
<td>2000 m</td>
<td>7.2 cm</td>
</tr>
</tbody>
</table>
Exprimer equation avec Gamma nord et Gamma est
lestarquitl, 5/19/2017
CORRECTION FOR DIFFERENTIAL TROPOSPHERIC DELAY

Model: tropo delay without horizontal gradient

\[ ZTD_{0-h} \]

\[ ZTD_{>h} \]

\[ \delta \text{tropo} = \frac{2 \cdot ZTD_{0-h}}{\sin \varepsilon} \]

Rough tropo delay modelled using T, P & P_{H2O} at closest meteo station:

But \( ZTD_{0-h} \) is difficult to model due to unknown water vapour content evolution with altitude → \( ZTD_{0-h} \) has to be solved!
Final Approach:
- Correction for earth curvature
- Correct or solve for reflection surface slope and direction
- Solve for TZD between the water surface and the aircraft
- N reflection points, N-1 equations

\[ \Delta_{ij} L_{R-D} \lambda = \Delta_{ij} \left\{ 2h \sin \varepsilon + \delta \text{ellip}(h, Az, \varepsilon) + 2h \cos(\varepsilon) \times (\gamma_N \cos(Az) + \gamma_E \sin(Az)) + \frac{2TZD_{0-h}}{\sin \varepsilon} + N . \lambda \right\} \]

Integer ambiguity search to solve for \{h, TZD_{0-h}, [\gamma_N, \gamma_E]\}
Analogy with standard method used in RTK
A model can be used to reduce the solution search space.
CARRIER AMBIGUITY RESULTS

Results not satisfactory at this stage:
Ambiguity solution not obvious due to « high » residuals (1-2 cm on several SV).
Possible reasons:
- uncorrected/mismodeled biases: antenna phase law, error in aircraft attitude ...
- The ADC desynchronisation was one extra unknown in the resolution.
- Single frequency approach : 19 cm ambiguity

Improvements for next time :
- Time aligned ADC
- Dual frequency (86 cm widelane)
POTENTIAL NEW APPLICATIONS OF CARRIER PHASE REFLECTOMETRY

- When solving for height, the following are resolved as well:
  - ZTD between the water surface and the GNSS carrier
    » The ZTD above the receiver can be resolved with the direct signal
  - Local water surface slope (2D) (either modelled or solved for)

Is the determination of these parameters useful for any scientific community?
For example determining water content in lower layers & determining the geoid slope by flying over a lake?
WRAP-UP

• With appropriate signal processing, carrier phase is usable for GNSS-R altimetry with high precision
  • Carrier phase use over rough sea: not demonstrated at this stage
• Ambiguity resolution:
  • Flat earth model only valid for h<100m.
  • For 100m<h<a few km: Flat earth model with corrections.
  • For h > few km: ray tracing might be needed.
  • Tropospheric delay has to be always accounted for.
  • Will be easier using dual frequency (L1-L2 widelane is 86 cm vs 19 cm for L1 carrier)
    • But only 18 GPS satellites with L2C, 12 with L5
• Potential novel applications for GNSS-R
  • 2 layer ZTD estimation: below receiver and above the receiver.
  • Geoid or Surface slope determination
Thank you for your attention
GNSS-SDR (1/2)
GNSS-SDR (2/2)
Very low elevation satellite (5°) +
Antenna tilted at 20° =
Direct signal leakage on the reflected
antenna (& vice-versa)
Analysis of the result of PRN 25

Elevation 25°: small direct signal leakage on the reflected antenna

→Correlation possible

Measured elongation = 9.5 cm

- IQ Diagram – SV 25
- Phase Shift – SV 25