GNSS Reflectometry for Studies of Surface Ice And Water Conditions

Roohollah Parvizi, Boris Pervan and Seebany Datta-Barua.
Illinois Institute of Technology

Supported by: NASA award NNX15AV01G
Outline

• Motivation
  – Why GNSS-R

• Objective
  – Detecting GNSS-R

• Background
  – Delay Doppler Map

• Method
  – What are our sensors
  – Data Campaigns
  – Signal Processing

• Results

• Conclusion
Motivation

Icy road

[1]: https://www.bikebandit.com/blog/black-ice-the-invisible-winter-threat  
Motivation

[3]: https://www.wsj.com/articles/laser-eyes
[4]: https://www.teslarati.com/tesla-lidar-sensors-spotted-testing-palo-alto/
[5]: https://www.detroitnews.com/story/business/autos
LiDAR disadvantages:

- Expensive, costly.
- Unreliable for water surface and breaking waves.
- It is affected by rain.
- Low operating range (500-2000m).
Space
Weather
Lab

Motivation

Can we do better with GNSS?

- Lower cost.
- Widespread coverage and availability.
- Unaffected by precipitation and cloud cover.
- Potentially better resolution.
GNSS-R:

- The study of the characteristics of a reflected signal
Objective

- Detect reflected GNSS signals from the water/ice surface.
- Verify GNSS-R.

Verification sensors

Power and Electronics

Satellite \( PRN^i \)

Satellite \( PRN^j \)

Direct Signal

Reflected Signal

ICE

Water
Specular Point (SP): The point on the surface where the incident and reflected angles are equal.

\[ \alpha_r = \beta_i \]
Glistening Zone

Receiver

Glistening Zone

Receiver

Glistening Zone
Delay Doppler Domain

Iso-Range line

Iso-Doppler line

North

Sensor suite

Specular Point (SP)

East

Satellite

$PRN^i$

M. Martin-Neirea, A Passive Reflectometry and Interferometry System.
Spatial Domain and Delay Doppler domain

Iso-Doppler line

Iso-Range line

Scattered Power

C/A code chips delay

Doppler frequency

Delay Doppler domain

SP

Delay

Scattered Power

November 7, 2018
Sensor Suite

Weather Station

Reflect antenna

LiDAR

Camera
Test 2 Location

Sensor direction

North

$\phi = 208^0$
Test 5 Location

$\phi = 60^0$

Sensor direction

North
# Data Campaigns Info

<table>
<thead>
<tr>
<th>Data campaign info</th>
<th>Test 02</th>
<th>Test 05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>Tue Jan 23 14:35:48 2018</td>
<td>Thu Jul 05 12:13:28 2018</td>
</tr>
<tr>
<td>Sensor Location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latitude: 41.8388924° N</td>
<td>Latitude: 41.84066° N</td>
<td></td>
</tr>
<tr>
<td>Longitude: 87.603140° W</td>
<td>Longitude: 87.60698° W</td>
<td></td>
</tr>
<tr>
<td>Height: 3 m</td>
<td>Height: 3 m</td>
<td></td>
</tr>
<tr>
<td>Sample rate</td>
<td>5 MHz</td>
<td>5 MHz</td>
</tr>
<tr>
<td>USRP_dir RF gain</td>
<td>31 dB</td>
<td>31 dB</td>
</tr>
<tr>
<td>USRP_ref RF gain</td>
<td>31 dB</td>
<td>31 dB</td>
</tr>
<tr>
<td>USRP_dir inline gain</td>
<td>0 dB</td>
<td>30 dB</td>
</tr>
<tr>
<td>USRP_ref inline gain</td>
<td>30 dB</td>
<td>40 dB</td>
</tr>
<tr>
<td>Look direction (azimuth angle)</td>
<td>208° (southwest)</td>
<td>60° (northeast)</td>
</tr>
<tr>
<td>Condition</td>
<td>Ice</td>
<td>Water</td>
</tr>
<tr>
<td>Condition</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Post-Processing

• Verification:
  – Evaluate surface condition with weather station.
  – Determine where SPs are.
  – Compare SPs with LiDAR.

• Detection:
  – DDM for SP on the water/ice.
Sky Plot and SP-LiDAR, Test 2 (ice)

visible satellite on Lake Michigan for Almanac Week 974 1-23-2018 at 14:34-14:35

frame 0001 of LM test 01 West EN Jan 23 2018 at time 14:35
“PRN 28 is reflecting off the water”
Incoherent DDM for PRN 28 Test 5 (water), Method 1

Reflected Signal

Direct Signal

DDM-Processing

Problem:
- Weak and noisy signal: direct signal not acquired by SDR, reflected signal band unexplained.

Solution:
- Use auto-correlation peak to test the direct signal for acquisition.
  - Method 2: Incoherent integration.
    - 20 ms, 100 ms, 500 ms and 1s
  - Method 3: Coherent integration
    - Coherently 10 ms
  - Method 4: Differentially coherent integration
- Generate reflected DDMs for the Method (4) that successfully acquires direct signals.
Method 2: Incoherent DDM Processing

Incoming signal

\[ e^{-j\omega t} \]

\[ 90^\circ \]

\[ I \]

\[ Q \]

Correlator

\[ \sum \]

\[ (\quad)^2 \]

Coherent integration

Incoherent integration

\[ \sum \]
Method 3: Coherent DDM Processing

First 10 ms Of data

20 ms Of data

D1

Results for D1 = $P_1$

Second 10 ms Of data

D2

Results for D2 = $P_2$

Pick data set that has the maximum power.
Method 4: Coherent differential integration

Incoming signal

\[ e^{-jwt} \]

\[ I \]

\[ Q \]

\[ 90^0 \]

Correlator

\[ \sum \]

Coherent integration

\[ (\quad)^2 \]

\[ Z^{-1} \]

\[ Y_{k-1}^* \]

\[ Y_k \]

\[ Z_k \]

\[ |.|^2 \]
Evaluate Methods
for Direct signal at high and low elevations, Test 5

SKY plot
based on almanac info

SKY plot
based on real GPS data
Autocorrelation of Direct Signal, PRN 28

Incoherent integration, method 2

Coherent integration, method 3

Result: Methods 2 and 3 each result in acquiring the high elevation direct signal.
Low elevation satellite, PRN 22, Direct signal

Incoherent integration, method 2

Coherent integration, method 3

Result: Methods 3 does NOT result in acquiring the low elevation direct signal.
Low elevation satellite, PRN 22, Direct signal

Result: Method 4 results in acquiring the low elevation direct signal and high elevation direct signal (not shown).

Next: Use Method 4 to generate DDM for the reflected signal.
Method 4: Coherent differential DDM for PRN 28 Test 5 (water)

Band in C/A space partly mitigated.

Reflected Signal

Direct Signal

Acquired in C/A and Doppler.
Method 4: Coherent differential DDM for PRN 22 Test 2 (ice)

Reflected Signal

Direct Signal
Conclusion

• Coherent, non-coherent, and coherent differential methods were studied for both direct and reflected GNSS signals.
  • Coherent differential method did a good job acquiring the low elevation satellite direct signal.

• We generated coherent differential DDMs for the reflected water/ice surface.

• Future work:
  • Further analysis of coherent differential DDMs.
  • Synchronization of multiple sensors.
  • Combination of signal processing methods.
  • Using accurate clock for USRPs, such as GPSDO.

• Additional data campaigns throughout 2018!
Houshine Sabbagh Zadeh, Li Pan, Yang Su and Ningchao Wang for their advice and technical support.
Thank YOU.
Extra Slides
However, reflected peak chip and Doppler change with k.

**Reflected Signal**

**Direct Signal**

Acquired in C/A and Doppler.
Result: Reflected signal assumed comparable in noise to low-elevation direct signal. Methods 2 and 3 do NOT result in a correct DDM (i.e., peak is not at the specular point).
Method 3 Coherent DDM for PRN 28 Test 5 (water), 10 ms

Reflected Signal

Direct Signal
Method 4: Coherent differential DDM for PRN 28
Test 5 (water)

Result: Method 3 results in a DDM at the specular point (C/A chip 867). However, band in C/A still exists in the reflected DDM only.
Low elevation satellite, PRN 3, Direct signal

Coherent autocorrelation, 1ms

Coherent autocorrelation, 10ms
Low elevation satellite, PRN 3

Coherent differential Autocorrelation, 1ms, K=1

Coherent differential Autocorrelation, 1ms, K=2
Incoherent DDM Processing, previous work: “Method 1”

20 ms Of data

D1

First 10 ms Of data

1st ms

Coherent integration

Results from 1st ms

10th ms

Coherent integration

Results from 10th ms

20 ms Of data

D2

Second 10 ms Of data

1st ms

Coherent integration

Results from 1st ms

10th ms

Coherent integration

Results from 10th ms

Results from 1st ms

Results from 2nd ms

Results from 10th ms

\[ P_{in} = \sum_{i=1}^{10} P_i \]

\[ f_1 \]