Inter-Frequency Aiding to Improve GNSS Receiver Carrier Tracking for RO Applications

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GNSS Signal Propagation Effects: Ionosphere, Troposphere, Multipath
What Do Ionosphere, Troposphere, Foliage, and Multipath Have In Common?

Scintillation: amplitude, frequency, phase fluctuation
A Simple Simulation:
Sum of 2 Rays

Graph showing signal intensity and phase over time with Mod. Freq., Mod. Ampl., and C/N0 values.
We See Them In Ionosphere Effects
Troposphere Effects & Surface Multipath Reflections

2017-05-06 Haleakala
Mountaintop Radio Occultation (MRO)

“Half way” satellite radio occultation

Direct LOS GNSS Satellite
(provide reference signals)

Near/Below Horizon GNSS Satellite transmits multi-open signals

LEO Radio Occultation Satellite

Planetary Boundary Layer

High gain antenna
Directed towards horizon

Lone mountain peak above PBL
Surrounded by ocean

University of Colorado Boulder

2018 ICGPS RO
Maui, Haleakalā (10,023 ft)
MRO Experiment

Steerable high-gain antenna

Maui
Haleakala
Big Island

Non-obstructed viewing area
Data Collection Electronics (2015)
Inter-Frequency Carrier Doppler Relationship

\[ f_{L1} = 154f_0 \quad f_{L2} = 120f_0 \quad f_{L5} = 115f_0 \]

If there is **NO** atmospheric effect:

\[ f_{Li} = \lambda_if_0 \]

\[
\begin{align*}
    f_{di} &= \lambda_if_{d0} \\
    f_{\dot{d}i} &= \lambda_i\dot{f}_{d0} \\
    f_{ai} &= \frac{\lambda_i}{\lambda_j}f_{aj} \\
    \dot{f}_{ai} &= \frac{\lambda_i}{\lambda_j}\dot{f}_{aj}
\end{align*}
\]
Naive Carrier Doppler Scaling

\(\text{i}^{th} \text{Carrier PLL}\)

- **Correlators**
  - **Reference Generation**
  - **Estimators and Filters**

  \(f_{di} = \frac{\lambda_i}{\lambda_j} f_{dj}\)

  \(\hat{\phi}_i, \hat{f}_{di}, \hat{f}_{di}\)

  \(\hat{f}_{dj}, \hat{f}_{dj}\)

From \(j^{th}\) carrier PLL

Inter-Frequency Adaptive Carrier Tracking (I-FACT)

Multi-carrier State Vector:
\[
\hat{x}_{i,k} = \begin{bmatrix} \hat{\phi}_i & 2\pi \hat{f}_{di} & 2\pi \hat{f}_{di} \end{bmatrix}
\]
\[
\hat{x}_{i,k+1} = A_{i,k} (\hat{x}_{i,k} + L_{i,k} \Delta \theta_{i,k})
\]

Fundamental Carrier Doppler & Doppler Rate Estimation

Scale to L1/L2/L5 Carrier Doppler & Doppler Rate
\[
f_{di} = \frac{\lambda_i}{\lambda_0} f_{d0}
\]

\[\Delta \theta_i, \hat{\phi}_i, L_i, i = 1, 2, 5\]
Single-Frequency ACT (S-FACT)

Example GLONASS Tracking Result

- PRN 17 L2
- 05/06/2017 15:39:38 UTC

Graph showing C/No(dB-Hz) and Elevation (deg) over time (Sec) for different tracking results.
GLONASS
PRN 17 L2
05/06/2017
15:39:38 UTC
GPS PRN03 L2CM 05/06/2017 UTC 08:06:39

Critical region
GPS PRN03 L1
05/06/2017
UTC 08:06:39

Doppler (Hz)
Elevation (°)

OL
I-FACT
S-FACT
PIF
Septentrio

Time (Sec)
0 500 1000 1500 2000 2500 3000

2800
3000
3200
3400
3600

21
Conclusions

• Inter-frequency carrier aiding
  • More robustness than single carrier tracking
  • More accurate than open loop tracking

• Applicable to ionosphere/troposphere scintillation and multipath fading.
Acknowledgement

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<table>
<thead>
<tr>
<th>System Model</th>
<th>Carrier on the $i^{th}$ frequency</th>
<th>Virtual Fundamental Carrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{Li,k+1} = Ax_{Li,k} + n_{Li,k}$ (11)</td>
<td>$\Delta \theta_{Li,k} = H \Delta x_{Li,k} + v_{Li,k}$ (13)</td>
<td>$y_{k+1} = Ay_k + n_k$ (12)</td>
</tr>
<tr>
<td>Measurement Model</td>
<td></td>
<td>$\Delta \theta_{Li,k} = \lambda_i H \Delta y_k + v_{Li,k}$ (14)</td>
</tr>
</tbody>
</table>
Figure 1 Generalized multi-frequency tracking loop architecture.
Fundamental Carrier Doppler and Doppler Rate Estimation

\[ f_i = \lambda_i f_0 \]

\[ \lambda = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_5 \end{bmatrix} \]

\[ \tilde{f}_{d0} = (\lambda^T \lambda)^{-1} \lambda^T \begin{bmatrix} \hat{f}_{d1} \\ \hat{f}_{d2} \\ \hat{f}_{d5} \end{bmatrix} \]

\[ \tilde{f}_{d0} = (\lambda^T \lambda)^{-1} \lambda^T \begin{bmatrix} \hat{f}_{d1} \\ \hat{f}_{d2} \\ \hat{f}_{d5} \end{bmatrix} \]