Developments in Modern GNSS And Its Impact on Autonomous Vehicle Architectures

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Perception is Key To Autonomy

But Unaided Perception Struggle To Solve Autonomy Safely and Reliably

GNSS-Based Localization Can Help
Limitations of Standard GNSS

Provides Global Localization
Constellation of satellites transmits digital ranging codes that support accurate distance and time measurement

But Suffers from Limited Precision, Errors and Faults
Errors include Noise and Biases
Faults include outages, false transmissions, and spoofing

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionosphere</td>
<td>~3 m</td>
</tr>
<tr>
<td>Troposphere</td>
<td>~1 m</td>
</tr>
<tr>
<td>Orbit Error</td>
<td>~2 m</td>
</tr>
<tr>
<td>Clock Error</td>
<td>~2 m</td>
</tr>
<tr>
<td>others</td>
<td>~1 m</td>
</tr>
</tbody>
</table>
Developments in Modern High Precision GNSS
Multiple Independent GNSS Constellations

**Four Global Constellations**
- GPS (USA)
- GLONASS (Russia)
- Galileo (EU)
- BeiDou (China)

**Provides Redundancy**
- 7x over-provisioned increases availability
- Quad independent constellation redundancy enables cross-checking and resiliency to individual constellation failures

* Over SF over 24 hours.
Modern Signals Across Multiple Frequencies

**Triple-Frequency**

L1, L2, L5 Frequency Bands

L5 is regulated by the ITU as a Safety-of-Life Service, providing legal protection against interference, channel sharing, spoofing and jamming.

**Modernized Signals**

<100ms signal acquisition time

<10cm pseudorange noise

**Provides Redundancy and Boosts Performance**

Much improved performance on accuracy and convergence time. Protection against interference.

<table>
<thead>
<tr>
<th>Band</th>
<th>Constellation and signal</th>
<th>Range resolution [m]</th>
<th>Carrier phase lock mean [sec]</th>
<th>Freq protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Glonass L1OF</td>
<td>600</td>
<td>2</td>
<td>good</td>
</tr>
<tr>
<td>L2</td>
<td>Glonass L2OF</td>
<td>600</td>
<td>2</td>
<td>poor</td>
</tr>
<tr>
<td>L1</td>
<td>GPS L1CA</td>
<td>300</td>
<td>6</td>
<td>good</td>
</tr>
<tr>
<td>L2</td>
<td>GPS L2C</td>
<td>300</td>
<td>0.1</td>
<td>decent</td>
</tr>
<tr>
<td>L1</td>
<td>Galileo E1BC</td>
<td>100</td>
<td>0.1</td>
<td>good</td>
</tr>
<tr>
<td>L1</td>
<td>Beidou3 B1C</td>
<td>100</td>
<td>0.1</td>
<td>good</td>
</tr>
<tr>
<td>L5</td>
<td>Galileo E6BC</td>
<td>60</td>
<td>0.1</td>
<td>bad</td>
</tr>
<tr>
<td>L5</td>
<td>Beidou3 B3I</td>
<td>30</td>
<td>6 (?)</td>
<td>bad</td>
</tr>
<tr>
<td>L5</td>
<td>GPS L5, Galileo E5a/b, Beidou3 B2a</td>
<td>30</td>
<td>0.1</td>
<td>good</td>
</tr>
<tr>
<td>L5</td>
<td>Galileo AltBOC, Beidou3 AltBOC</td>
<td>5</td>
<td>0.1</td>
<td>good</td>
</tr>
</tbody>
</table>
Algorithms to Correct Errors and Faults

PPP-AR
10cm (1σ)
Converges in Minutes
Continent-Scale Coverage
Modern Technique, Target for Automotive

Injests Signals from GNSS Monitoring
Requires using fixed GNSS receivers that monitor the GNSS signal

Corrects Noise, Errors and Faults
Much improved performance on accuracy and convergence time. Protection against interference.
Ground-Based Monitoring Networks

Corrections Networks
Continent-wide ground station networks continuously monitors the GNSS signal and the local atmosphere

Estimates Errors and Faults
Ground stations can estimate errors and detect faults
- Ionosphere delays
- Troposphere delays
- Clock drift
- Orbital drift
- Hardware biases and delays

Enables Precision and Integrity
Provides corrections service to achieve continent-wide decimeter-level accuracy
Fault monitoring enables integrity outputs in the form of alerts that signal when GNSS cannot guarantee performance within bounds.
Data Standards For Corrections in 5G Rollout

5G Standardization for Interoperability

Corrections format containing error corrections (clocks, orbits, iono, tropo, etc…) and integrity information (fault status, etc)

Being integrated in the NR standard for 5G deployments.

Corrections is becoming a Utility

Corrections information is becoming part of the cell infrastructure delivered globally.

Carriers are providing corrections as a utility, interoperable between devices and suppliers.

High Precision and Integrity Outputs is becoming commercially available to automotive.
Accurate Reference Frame and Reference Ellipsoid

Some parts of California coastline moves ~10cm per year

New models (ITRF2014, NOAA’s HTDP, etc.) takes into account dozens of variations in earth crustal activity and tracks crustal drift over time.

High Precision Maps can be Globally Localized

Features on High Precision Maps can be accurately localized on a global, absolute reference frame.
Mass-Market Automotive Chipsets

~$10 Automotive Grade Multi-Frequency Corrections-Ready GNSS Modules

Teseo-LIV3R ROM Module
GNSS solution for accurate tracking
Putting It All Together
Results
Steady March of Accuracy
Select Mass Market Automotive GNSS Performance since 2000

**TABLE II**
Select data points that show on-road GNSS performance improvements between 2002-2019.

<table>
<thead>
<tr>
<th>Source</th>
<th>Year of Data</th>
<th>Data Set</th>
<th>Const.</th>
<th>Freq.</th>
<th>Receiver Type</th>
<th>GNSS Corrections</th>
<th>Env.</th>
<th>Accuracy</th>
<th>Availability</th>
<th>Outage Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>[50]</td>
<td>2000</td>
<td>2 hours</td>
<td>GPS</td>
<td>L1</td>
<td>Survey</td>
<td>None</td>
<td>Urban</td>
<td>10m, 74%, Lateral</td>
<td>28%</td>
<td>4.7 min, Worst-Case</td>
</tr>
<tr>
<td>[51]</td>
<td>2010</td>
<td>186 hours</td>
<td>GPS</td>
<td>L1</td>
<td>Survey</td>
<td>None</td>
<td>Urban, Suburban, Rural, Highway</td>
<td>-</td>
<td>85%, Code Phase Position (HDOP &gt; 3)</td>
<td>28 sec, 95%, Code Phase Position (HDOP &gt; 3)</td>
</tr>
<tr>
<td>[47]</td>
<td>2017</td>
<td>1 hour</td>
<td>GPS, GLO, Gal</td>
<td>L1, L2</td>
<td>Mass Market</td>
<td>PPP-RTK</td>
<td>Suburban</td>
<td>0.77m, 95%, Horizontal</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>[52]</td>
<td>2018</td>
<td>355 hours</td>
<td>GPS, GLO</td>
<td>L1, L2</td>
<td>Survey</td>
<td>Net. RTK</td>
<td>Mostly Highway</td>
<td>1.05m, 95%, Horizontal</td>
<td>50% Integer Ambiguity Fixed</td>
<td>10 sec, 50%, 40 sec, 80% Fixed</td>
</tr>
<tr>
<td>[53]</td>
<td>2019</td>
<td>2 hours</td>
<td>GPS, Gal</td>
<td>L1, L2</td>
<td>Research SDR</td>
<td>Net. RTK</td>
<td>Urban</td>
<td>0.14m, 95%, Horizontal</td>
<td>87% Integer Ambiguity Fixed</td>
<td>2 sec, 99%, Fixed</td>
</tr>
<tr>
<td>Swift Navigation</td>
<td>2019</td>
<td>12 hours</td>
<td>GPS, Gal</td>
<td>L1, L2</td>
<td>Mid-Range</td>
<td>Proprietary, Continent-Scale</td>
<td>Mostly Highway</td>
<td>0.35m, 95%, Horizontal</td>
<td>95% CDGNSS</td>
<td>-</td>
</tr>
</tbody>
</table>
Step Change in Safety of Life of Life guarantees provides fault alerts with very low probability of false negative for meter-scale faults. Green Circle represents 1e-7 integrity guarantee [GMV MagicPPP].
Impact on Autonomy Architectures
SAE Level 2 Vision-based Systems

GNSS provides Lane Determination with High Certainty

Safe Lane-Level Maneuvers such as changing lanes into an exit lane.

Protection against dangerous vision errors such as false lane detections steering the car into highly hazardous areas.
GNSS Complements LiDAR

LiDAR localization experiences errors and faults, often in environmental conditions where GNSS works particularly well, such as areas with little geometry (freeways!)

Provide Localization when LiDAR struggles such as on freeways

Provides Fallback during Outages such as degraded operation if LiDAR faults

Independence of GNSS drives localization safety case since the error modes of GNSS is not correlated to the error modes of perception sensors
Looking to the Future: Beyond One Vehicle

The GNSS Ecosystem Enables Vehicle to Vehicle and Vehicle to Infrastructure Collaboration to Overcome Occlusion, Share Perception, and Collaborate Between Vehicles and Manufacturers
Thank you!

More details in our paper!
“Developments in Modern GNSS and Its Impact on Autonomous Vehicle Architectures”

We’re happy to take questions by email!
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