UNMANNED SYSTEMS WEEK

WELCOME TO
POSITIONING, NAVIGATION, AND GUIDANCE FOR UNMANNED SYSTEMS

Monday, June 2, 2014
11 am–12:30 PDT
Noon–1:30 pm Mountain
1 pm–2:30 pm Central
2 pm–3:30 pm Eastern

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WELCOME TO
Positioning, Navigation, and Guidance for Unmanned Systems

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Director of Core Cards
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Andrey Soloviev
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Executive Vice President
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Co-Moderator: Lori Dearman, Sr. Webinar Producer
Who’s In the Audience?

A diverse audience of professionals registered from 43 countries, 30 states and provinces representing the following industries:

- **21%** GNSS Equipment Manufacturer
- **17%** Professional User
- **17%** System Integrator
- **17%** Product/Application Designer
- **28%** Other
Welcome from *Inside GNSS*

Glen Gibbons
Editor and Publisher
*Inside GNSS*
Positioning, Navigation, and Guidance for Unmanned Systems

Demoz Gebre-Egziabher
Aerospace Engineer and Mechanics Faculty
University of Minnesota
Poll #1

What application are you interested in using unmanned systems for? (Select all that apply)

- Air
- Land
- Marine
Overview of Unmanned System
PNT Requirements

Demoz Gebre-Egziabher
Aerospace Engineer and
Mechanics Faculty
University of Minnesota
Unmanned Systems

- Vehicles without a human operator onboard
  - Unmanned Aerial Vehicles (UAV)
  - Unmanned Ground Vehicles (UGV)
  - Unmanned Marine Vehicles (UMV)
- Ideal for the 3-Ds tasks: Dangerous, Dirty and Dull
- Position, Navigation and Timing (PNT) performance metrics
  - Accuracy
  - Availability
  - Continuity
  - Integrity

- PNT Requirements depend on vehicle and operation
  - Example 1: UAV in Precision agriculture (Accuracy)
  - Example 2: Car platooning (Integrity)

- Can be as stringent as manned vehicle requirements
Performance Metrics

- **Availability**
  - Availability is defined (or computed) as the fraction of time a navigation system is providing position fixes to the specified level of accuracy, integrity and continuity.

- **Accuracy**
  - Accuracy or Navigation Sensor Error (NSE) is defined as the difference between the position estimated by the navigation sensor and the true position of the aircraft which is only exceeded 5% of the time in the absence of system failures.

- **Integrity**
  - Integrity risk is the likelihood of an undetected navigation error or failure that results in hazardously misleading information.

- **Continuity**
  - Continuity risk is the probability of a detected but unscheduled navigation function interruption after an operation has been initiated.
Webinar Objectives

- What do these performance metrics mean?
- How are they measured?
- What are the software (algorithm) and hardware solutions to achieve these?
- How are the specific PNT requirements achieved in the air, land and marine domain?
- Defined as how often a position, velocity and time solution is available

- For an Unmanned System (US), the requirement is typically *always available in real-time*
GNSS solution availability is governed by:

- View of the sky
- Signal quality
Multi-Constellation Support
- Tracking everything up there is the simplest approach to being able to maximize the number of epochs with a position solution

In an airborne situation, GPS alone may be sufficient
- But perhaps not if significant banking occurs

GNSS not just GPS
- Include GLONASS, Beidou, Galileo

By 2020, both Beidou and Galileo are expected to be fully operational
In an urban canyon, the addition of GLONASS can enable a position to be computed when GPS alone would not

- Doesn’t provide ideal positioning geometry, but any position is often better than no position
Today in Asia, Beidou coverage is currently quite good, with the high elevation geostationary satellites being especially valuable.

Beidou Visibility – Gold Coast, Australia
If there is a failure in one constellation, you have others to rely on.

For each constellation, supporting dual or triple frequency increases the number of measurements available
- Also provides opportunity for higher accuracy solutions by removing ionospheric errors

More measurements also means you can be more selective in choosing which ones contribute to the solution
- More statistical analysis of “good” and “bad” measurements
Even with line of sight to a sufficient number of satellites, interference can render the signals in space inaccessible or useless.

The flip side of multi-constellation and multi-frequency support can be interference susceptibility:
- Depends on how the receiver is designed
- How wide are the paths? Does GPS L1 share a path with GLO L1, or is GLO L1 separate?
- Depends on the antenna used
- If you aren’t using all the frequencies, do not use a wide band antenna.

Interference conditions on a UAV can be especially challenging:
- Lots of electronics packed into a small area
- Other sensors onboard, like radar, can be interference sources
- Telemetry systems
Frequencies of Interest

- **Telemetry:** 1492-1525 MHz
- **LSQ L10 Tx:** 1526-1535 MHz
- **LSQ H10 Tx:** 1545-1555 MHz
- **Communication Satellites:** 1610-1626.5 MHz
- **Inmarsat Tx:** 1626.5 – 1646.5 MHz

- **Inmarsat Rx:**
  - 1535.xx MHz
  - 1537.xx MHz
- **Inmarsat Rx L6 (SAR):** 1544 MHz

- **Radar:** Up to 1150 MHz
- **Amateur Radio:** 1260-1270 MHz

- **GLONASS L1:**
  - 1575.42 MHz
  - 1598 MHz
  - 1606 MHz
- **GLONASS L2:**
  - 1227.6 MHz
  - 1278.75 MHz
- **Radar:** Up to 1150 MHz

- **E1 A/B/C:**
  - L1-M, L1C 1575.42 MHz
- **E5 B2a:**
  - 1191.795 MHz
  - 1201.743 MHz
- **E5b B2:**
  - 1207.14 MHz
- **E5a:**
  - 1176.45 MHz
- **E5:**
  - 1201.743 MHz
  - 227.6 MHz
- **E6:**
  - 1278.75 MHz
- **B3:**
  - 1268.52 MHz
Anti-Jam Antenna: Null Steering

- A Controlled Reception Pattern Antenna (CRPA) is multiple antenna elements that are used to exploit spatial diversity
- Digital spatial processing is used to modify the apparent gain and phase of the antenna elements to create a new adaptively changing antenna pattern that creates nulls in the direction of the interfering signal
- N-1 degrees of freedom, where N is the number of antenna elements

NovAtel’s GAJT (N = 7)
Some applications cannot bear the size or weight of an anti-jam antenna

Need to rely on receiver design only then

Mitigation techniques on the receiver, for example:

- Digital filtering? (provided you are not saturated)
- Narrow band design and independent signal tracking – let’s you “turn off” problem frequencies
Multipath is often a dominant error source
- Especially in urban areas
- With vehicles approaching large installations or buildings
  - Refueling a small craft from a large tanker
  - Mining vehicle close to a pit wall
- Especially an issue with high sensitivity receivers

With GNSS only, it can be difficult to identify and remove or adequately de-weight multipath-ed measurements

The correlator used in the receiver is a key defense against multipath

Direct reflected signals hard to detect

Antenna design also key to multipath performance
Track the signals that are valuable to you!

Protect those signals
- Shielding
- Receiver RF design
- Antenna design
Ask the Experts – Part 1

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Poll #2

In which of the following unmanned system operating domains are the PNT requirements most stringent? (Please select one)

• Air
• Land
• Marine
• It depends on the operation
Accuracy Requirements

Andrey Soloviev
Principal
QuNav
There are **no general requirements**, accuracy is defined by a **specific application**.

- **Precision agriculture**
  - **Centimeter-level accuracy**
- **Autonomous driving**
  - **Decimeter-level accuracy**
- **UAVs**
  - **Meter-level accuracy**
- **Autonomous marine vessels**
  - **0.1-2 meters**
## GNSS Positioning Techniques

<table>
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<th>Positioning Technique</th>
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<td>~ 10 meters</td>
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<td>Meter-level</td>
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<td>Precise Point Positioning (PPP)</td>
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<tr>
<td>Real-Time Kinematic (RTK) solution</td>
<td>Centimeter-level</td>
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- GNSS can generally meet accuracy requirements when adequate satellite geometry is available (open-sky, suburban areas);

- Otherwise, augmentation with other sensors is required (tree-covered applications, dense urban areas, indoors, underwater)
Main Positioning Techniques

• Stand-alone solution
  - GNSS receiver tracking loops
  - Pseudoranges → Code-carrier smoothing → Least mean square (LMS) position estimation
  - Carrier phase

• Satellite-Based Augmentation Systems (SBAS)
  - GNSS receiver tracking loops
  - Pseudoranges → Code-carrier smoothing → Corrections → LMS position estimation
  - Carrier phase
• Precise Point Positioning (PPP)

\[ \varphi = (e_{SV}, R) + b + \varepsilon \]

- Carrier phase adjustment
- Satellite orbit and clock corrections (e.g., from IGS; Iono (dual-frequency, SBAS))
- Pseudoranges

- Kalman filter
  - State vector
  - Initialization
  - Noise, multipath
  - Position
  - Residual adjustment error (tropo, integer ambiguity)
• **Real-Time Kinematic (RTK) solution**

**Rover receiver**

Base receiver

Pseudoranges, Carrier phase

Double differencing

Pseudoranges, Carrier phase

Ranges

Phase

Code-carrier smoothing

Float solution

Resolution of integer ambiguities (LAMBDA)
- Other motion states have to be estimated for *trajectory control* and *trajectory capture*:
  - Velocity, acceleration, attitude

- Similar to positioning, *accuracy requirements* are *application specific*

  Example: Geo-registration with UAVs

  *Attitude requirements are height-dependent*

  ![Diagram showing position accuracy: 1 meter, h = 1 km, and h = 100 m with angle errors of δα = 1 mrad and δα = 10 mrad.](image)
**GNSS Velocity Estimation**

- **Possible Approaches:**
  - Position differencing
  - Use of Doppler frequency
  - Estimation of velocity from temporal changes in carrier phase

- **Estimation of velocity from carrier phase**

  **Carrier phase measurement**
  \[
  \varphi = \rho + \lambda N + \delta t_{rcvr} + \varepsilon + \eta
  \]
  - Ambiguity
  - Clock bias
  - Noise & multipath
  - Atmospheric delays & SV clock

  **Temporal differencing**
  \[
  \Delta \varphi = -(e_{SV} \Delta R) + SV \text{ motion terms} + \Delta \delta t_{rcvr} + \Delta \varepsilon + \Delta \eta
  \]
  - Velocity estimation
- **Example Test Results**

Flight trajectory

East displacement, m

North displacement, m

East velocity error, m/s

North velocity error, m/s

- $\text{std} = 2.6 \text{ mm/s}$
- $\text{std} = 3.7 \text{ mm/s}$
Use of multiple antennas and carrier phase interferometry

- Antenna 1
- Antenna 2
- Antenna 3

{A, B, C} resolved in the navigation frame of reference

{A, B, C} resolved in the body frame (pre-measured)

Attitude accuracy:

\[ \sim 1 \text{ cm/ (size of the multi-antenna system)} \]

Constrained ambiguity resolution (known length of the baseline)

\[ A \] resolved in the navigation frame of reference

Limited accuracy for small-size autonomous vehicles (augmentation with inertial may be required)
DGNSS for Unmanned Marine Vessels

Stephen Browne
Executive Vice President
Veripos
Limited number of production UMVs currently operating, and several prototype UMVs undergoing test and evaluation with other prototypes in the planning stages.

UMV missions:
- Military
- Offshore Oil & Gas
- Scientific
- Cargo & Transportation

Photo courtesy of Rolls Royce and Bloomberg Media

Photo courtesy of Aeronautics Defense Systems Ltd.

Photo courtesy of Liquid Robotics & Marinelink.com
- Robust, reliable and redundant DGNSS positioning system, most likely integrated with INS:
  - Designed to prevent single-point-failures
  - High-accuracy PPP DGNSS solution
  - Marine Environmental Considerations
  - Position Outputs
  - INS Integration
  - Heading Capability
  - Data logging

Photos courtesy of Autonomous Surface Vessels Ltd.
(ASV Unmanned Marine Systems)
GNSS Challenges

- GNSS Issues & Challenges:
  - Multipath
  - Dynamic Motion
  - Antenna location and type
  - Interference
  - Physical system integrity
  - Position integrity, accuracy & repeatability
  - Antenna Blockage caused by platforms

Photo courtesy of Subsea 7

Photo courtesy of Textron Systems
Multipath & Motion Issues

- Multipath issues:
  - Antenna height in relation to water surface
- Motion issues:
  - High dynamic range of motion in various sea states
  - Rapidly changing GNSS constellation elevations
  - Corrections links
- These issues make an argument for an integrated INS/DGNSS solution
Receiver & Antenna Considerations

- Receiver & Antenna Issues:
  - Small vessel design & mast
  - System physical integrity: Integrated Pod system or separate receivers & antenna
  - Receiver capability
  - Analysis and selection of antenna type
  - Interference rejection criteria

Photo & image courtesy of NovAtel Inc.

NovAtel GAJT Antenna
Interference in the Marine Environment can generally be classed as in-band interference and out-band interference

- Causes of In-band interference
- Causes of Out-band interference

Extra Consideration: Data-link systems

Receiver technology, antenna type and mounting location (again)

DGNSS & INS integration

Courtesy of the U.S. Department of Commerce
The integrity of the DGNSS position will be influenced by the operational criteria of a specific mission type, for instance:

- Operations requiring absolute accuracy
- Operations requiring position stability robustness
- Multi-mission configurable vessels will require both
As with all marine DGNSS operations, the prevention of single point failures will be a key design criteria. There are several areas to be addressed, as follows:

- Multi-constellation capability
- Capable of utilizing multiple correction sources simultaneously
- Integration of INS & DGNSS
- Redundant systems
- Different and complimentary systems

Photo courtesy of Veripos Ltd.

Veripos LID6-GG2 IMU
Sources and References

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- Weds, June 4\(^{th}\): GNSS/Inertial + Integration for Unmanned Systems
- Fri, June 6\(^{th}\): Unmanned Solutions & Applications Day

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Poll #3

If all regulatory framework is in place, When do you see yourself using unmanned systems? Within: (Please select you one)

- 1 year
- 2 years
- 3 years
- 4 years
- 5 years