Resilient Alternative PNT Capabilities for Aviation to Support Continued Performance Based Navigation

Presented by Sherman Lo
International Technical Symposium on Navigation & Timing
ENAC, Toulouse, France
November 17, 2015
GNSS is the foundation of Modernized Airspace

- GNSS will be the primary navigation source in aviation
  - NextGen, SESAR

- Improves airspace efficiency & capacity to meet future needs
  - Handle 2-3 times current traffic level
  - More efficient flight operations

- GNSS is vulnerable to interference & other attacks
Interference Range vs. Power

5 W jammer can affect GNSS for 50 km or more
Terrestrial Transmitter for Resilient APNT

• Alternative Positioning Navigation & Timing (APNT) program is developing terrestrial navigation to support future airspace

• Terrestrial transmitter are more robust to jamming (power & proximity)

• Line of sight (LOS) & multipath limit performance
Power/Proximity Benefit of Terrestrial Station

5 W jamming has only a small effect on a nearby ground station (< .7 km, 250 W, < 1.5 km 50 W))

Terrestrial Transmitter

5 W jammer on GNSS
Current US APNT Program Plans

• Distance measuring equipment (DME) has long been the primary source of navigation for most commercial aviation

• DME is near- to mid-term APNT
  – Multiple DME (DME/DME) positioning

• Long-term APNT is “going to concept”
  – Refine requirements & concept development
  – Target implementation in 2025
Outline: The Road to Future APNT

1. DME/DME & Future APNT

2. Enhanced DME (out of band) pseudolites
   - 2A. Pulse Pair Position Modulation (PPPM)
   - 2B. Carrier Phase

3. Improving Coverage: Ranging from other terrestrial aviation signals (Automatic Dependent Surveillance Broadcast (ADS-B), L-band Digital Aeronautical Communication System (LDACS))

4. Multipath Mitigation
1. Today’s Distance Measuring Equipment (DME) Transponders


- DME
- Tactical Air Navigation (TACAN)

(Colors indicate equipment age)
NextGen Near-Term DME/DME

• Current US DME system has coverage holes at altitude (18000 ft & 24000 ft) when using multiple DME (DME/DME) for RNAV 1.0
  – Area Navigation (RNAV) of 1.0 nautical mile
  – Need inertial reference unit (IRU)

• FAA NextGen examining the number of new transponders needed to provide serve RNAV 1.0 enroute with DME/DME and some major terminal area
Long-Term APNT to Improve APNT Capabilities

• Increased performance: terminal area & approach operations (accuracy, coverage, capacity, etc.)

• Increased resilience & robustness: signal diversity, redundancy, authentication

• Additional services: data capacity
Flight Test & Demonstration of APNT Technologies at Ohio University

- Rockwell-Collins DME2100 interrogator
- SDR recording of UAT, 1090-ES, DME Rx & Tx
- GPS truth

Source: Wouter Pelgrum, Ohio U.
2. Enhanced DME (eDME)

• Enhanced DME provides passive ranging & data in addition to traditional DME functions

• “Non priority” DME pseudolite using pulse pair position modulation (PPPM)
  – Compatible with existing ground equipment (DME transponder)

• “Priority” DME pseudolite using carrier phase modulation
  – Provides higher accuracy, multipath mitigation
  – Requires stabilized carrier & phase modulation

• Designs are compatible: ranging component can be the same pulse pairs
2A. Non Priority DME Pseudo Ranging using Pulse Pair Position Modulation (PPPM)

- Use nominal DME transponder operations – like aircraft on the ground
  - Create pseudorandom series of reply pulse pairs in time – range & data
- Preliminary design uses < 20% of DME capacity
  - Preliminary design 500 pulse pairs per sec (ppps): 150 for range/sync, 350 for data (~20 aircraft); typical DME transmits 2700 ppps

Non Priority eDME Example

DME Transponder

DME PPPM Generator

Δt₃  Δt₂  Δt₁  Δt₀

Reply to aircraft interrogation
Reply to DME PPPM Generator
Implementing DME PPPM Pseudolite

TX is DME transmission, RX is USRP or Pseudolite transmission

DME/TACAN MM7000
- TX: 1kW (+60dBm)
- RX: -21dBm
- TX: +30dBm
- RX: -21dBm
- TX: 0dBm
- RX: +9dBm
- TX: -20dBm
- RX: +10dBm

Directional Coupler 30dB

30dB Attenuator

Isolator

USRP

Computer Playback Signal

GPS steered Clock 10 MHz & PPS

TX is DME transmission, RX is USRP or Pseudolite transmission
Creating DME PPPM Pseudolite Generator

DME PPPM generator couples into DME antenna
No need to change any existing DME hardware/software
Static Measurement of Sync Pulse Pairs (at Ground Station)

Initially little traffic added

Interference from Morse Code Station Ident (every 30 sec for ~ 5.6 sec)

Traffic added to 2700 ppps: should have ~ 75% replies

Drop out every 29 sec (restart)
Percentage Sync Pulse Pairs Measured in Flight (March 10 PM)

On airport ground
Banked away from DME

Similar performance in-air as ground but with more variations
Sync pulse pair reception & correlation follows the overall performance of the DME.
Map of Percentage of Sync Pulse Pairs Received
2B. Priority eDME using Stable Carrier

- Having precise carrier phase control enables many new DME features
  - Very low displacement measurements
  - Extended tracking & integration
  - Multipath bounding
  - Pseudo ranging & Data transmission

DME pulse pairs generated using continuous carrier phase (no set phase/envelope relation)

Existing transponders have $\sim 10^{-6}$ sec/sec oscillators

eDME carrier phase needs more stable carrier to track cycles between DME pulse pairs

Based on slide from: Wouter Pelgrum, Ohio U.
Priority eDME Example

All Pulses: Stable Carrier Phase
Beat/Sync Pulses: Phase Shift
Keying (PSK)

Reply to aircraft interrogation
Reply to DME PPPM Generator

Modified DME Transponder

Δt₃  Δt₂  Δt₁  Δt₀
Implementing eDME Carrier Phase

- Built around modified Moog MM-7000
- Custom FPGA trigger generator & phase modulator
- SDR RF file-playback traffic generator
- SDR RF file-playback PPPM generator
- SDR for optimized ranging, signal-in-space monitoring & validation

Source: Wouter Pelgrum, Ohio U.
eDME Ground Setup

Source: Wouter Pelgrum, Ohio U.
Priority Beat Signal (Pseudo range) Performance

Large differences in multipath on different radials

250 ppps, 0.4 sec averaging (100 pulses)
Better than specified DME range error (370 m)

Source: Wouter Pelgrum, Ohio U.
DME Carrier Phase Performance

Note: depicted performance without level arm correction, and using approximate tropo correction

Source: Wouter Pelgrum, Ohio U.
3. Ranging Using Other Terrestrial Aviation Signals

- Two challenges with terrestrial signals for aviation navigation are: low altitude coverage & multipath

- Using other signals to address these challenges

- Signals being studied
  - Automatic Dependent Surveillance Broadcast (ADS-B): 1090 MHz Mode S Extended Squitter (ES), Universal Access Transceiver (UAT)
  - L-band Digital Aeronautical Communication System (LDACS)
ADS-B Radio Station (RS) Antenna

Directional 1090 MHz Mode S Extended Squitter (ES) antennas (90°)

Omni-directional Universal Access Transceiver (UAT) antenna
UAT Passive Ranging

UAT Frame = 1 Second

Guard Time 6 ms

Ground Segment 176 ms

Guard Time 12 ms

ADS-B Segment 800 ms

Guard Time 6 ms

Message Start Opportunities (MSOs) every 250 μsec

MSO 0

MSO 752

MSO 3951

From RS only, contains station location & time of transmission (TOT). 1-4 transmissions/sec from each station.

From both aircraft & RS. No TOT. Transmitted as necessary. Can also be used for ranging

Ground segment has 32 transmission slots, message designed to support passive ranging
Aircraft ADS-B Rack Shelf

- 1090 Mhz Filter
- Splitter (RF)
- Splitter (1 pps)
- UAT Filter
- 2 USRP software radios
- Limiter
- In line Amp
- Splitter (10 MHz)
- Switch
- Power adapter
UAT Pseudorange Error (with tropo, GPS clock, & bias removed)

Ranging error (Tropo & clock correct), with static bias removed

Measured accuracy < 50 m compares well to DME Range Error: 370 m (spec)
Horizontal Positioning with UAT

March 11, 2015 PM
~ 10500 ft MSL

March 12, 2015 AM
~ 3300 ft MSL

Error (m)
Mean: 29.1 m, Std = 21.2 m

DOP < 10, Within 10 km

Error (m)
Mean: 30.5 m, Std = 35.0 m
4. Multipath Assessment

- Multipath Effects – where do we have bad multipath errors & why

- Multipath Characterization – what is the source of the multipath

- Multipath Mitigation Strategies – what are reasonable ways of reducing or alerting for multipath
DME Two Way Range at 10000 ft (0.4 sec average)

Source: Wouter Pelgrum, Ohio U.
DME Two Way Range at 10000 ft (100 sec average)

Source: Wouter Pelgrum, Ohio U.
Proper siting is essential!

Source: Wouter Pelgrum, Ohio U.
Localization of reflectors

• Precise estimation of parameters allows for localization of reflection source (assuming single bounce)

Source: Nicolas Schneckenburger, DLR.
Summary of DME Multipath Mitigations

<table>
<thead>
<tr>
<th>Mitigation</th>
<th>Avionics Changes</th>
<th>Ground Changes</th>
<th>Effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational Changes (identify high multipath area, poor siting, weak LOS situations, etc.)</td>
<td>Maybe/None</td>
<td>None</td>
<td>Varies</td>
</tr>
<tr>
<td>Averaging (Simple)</td>
<td>Maybe/None</td>
<td>None</td>
<td>Depends on geometry but effective for “good” multipath geometries</td>
</tr>
<tr>
<td>Fast Rise Time (&amp; improved signal proc)</td>
<td>Yes (if on interrogation)</td>
<td>Yes/Maybe (if on reply)</td>
<td>Reduce multipath by $\sim \frac{1}{2}$ (if within specs)</td>
</tr>
<tr>
<td>Carrier processing</td>
<td>New avionics</td>
<td>Yes</td>
<td>Affects only reply, not interrogation</td>
</tr>
<tr>
<td>Extended Averaging</td>
<td>New avionics</td>
<td>Yes</td>
<td>Allow for much longer averaging times</td>
</tr>
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Summary

• Terrestrial system are attractive from a resilience to interference
  – Comes with challenges: multipath, line of sight

• eDME concepts have been prototyped & tested
  – eDME PPPM compatible with existing equipment
  – eDME carrier phase provides increase performance

• Several attractive L-band aviation signals may be used for APNT and are being tested (UAT, 1090 MHz Mode S ES, LDACS)

• Key challenges are being addressed in our testing
Thank You

- March 2015 APNT Technology Flight Test
- Ohio University: Kuangmin Li, Wouter Pelgrum, Adam Naab-Levy, Jamie Edwards (Pilot)
- Stanford University: Sherman Lo, Yu-Hsuan Chen
Acknowledgements & Disclaimer

• The authors gratefully acknowledge the support of the FAA. We also appreciate the feedback and inputs of the members of the APNT technical team.
  • Stanford: Yu Hsuan Chen
  • Ohio University: Wouter Pelgrum, Kuangmin Li, Adam Naab-Levy, Jamie Edwards
  • DLR: Nicolas Schneckenburger
  • FAA/Contractor: Mitch Narins, Robert Lilley, Robert Erikson
  • Moog: George Weida, Achim Soelter

• The views expressed herein are those of the authors and are not to be construed as official or any other person or organization.