Antenna and aircraft radiating models for a GNSS multipath pseudo-range error model

ITNST, Young Researcher Session, Toulouse, France, November 15th

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1. Introduction: context and objectives

- Use of GNSS to navigate with integrity on airport surface
  - Attractive means
    - It is currently used for En-Route to Precision Approaches.
  - Drawbacks
    - No GNSS surface multipath error model is yet standardized for integrity monitoring during taxi operations.

- Objectives of the thesis
  → Provide a GNSS multipath error model for aircraft surface operations
  → Contribute to the standardization of this model
  → Test the model with a hybridization with other sensors

- ENAC previous works on this topic

- Objective of this talk
  Present identified GNSS antenna models limits in the context of aircraft surface navigation
  The simulation results are here presented for L1 but simulations will also be performed for L5.
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2. GNSS multipath error model for aircraft surface navigation

2.1 The multipath simulator: deterministic prediction [Chen10]

Simulator principle for estimating multipath pseudo-range errors
- 2 main blocks
  - The multipath generator predicts the electromagnetic fields computed by Physical Optics and Geometrical Optics
  - The GPS receiver simulator predicts the GPS range error

Rectangular facets, metallic, dielectric or multilayer materials

Static or dynamic

For each multipath:
- Amplitude
- Delay
- Phase
- Doppler shift

Correlator outputs
- Tracking only
- Parameters consistent with civil aviation receivers
2. GNSS multipath error model for aircraft surface navigation

2.1 The multipath simulator: deterministic prediction [Chen10]

- PO is a current asymptotic method valid at high frequencies which allows computing the scattering from a surface
  - the signal wavelength is small in comparison to the size of the reflectors.
- First-order interactions
  - Each illuminated surface generates reflected field i.e. each illuminated facet is at the origin of one multipath,
  - Ground is modeled via image theorem.

First-order façade reflection

Ground modeling for first-order reflection
2. GNSS multipath error model for aircraft surface navigation

2.1 The multipath simulator: deterministic prediction [Chen10]

- For second-order interactions we use a PO-based method
  - Facades interaction: GO + PO
  - Ground modeling: image theorem + PO
2. GNSS multipath error model for aircraft surface navigation

2.2 Hybrid deterministic statistical prediction [Chen10]

We base the statistical simulator on the deterministic simulator via Monte Carlo (MC) simulations. The uncertainties in the configuration are taken into account via adding a statistical variability to the 3D scene.

### Statistical parameters
- Building horizontal position
- Building horizontal orientation
- Building height
- Building material
- Building material thickness
- Ground material
- Scene altitude

**Diagram Description:**
- Statistical Parameters
  - Environment Generator
  - Multipath Generator
  - GPS Receiver Simulator
- Environment Modeling
- Convergence Test
- Mean and Variance of the Range Errors

While no convergence of the mean and variance of the range errors
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3. GNSS antenna models

3.1 Antenna effect on multipath computation

Reference antenna model: transfer function in all direction of arrival but complex

- Simpler model:

- **Amplitude**
  The multipath amplitude is the voltage induced by the multipath at antenna port. It can be characterized via the effective height and the incident electric field.

  \[ V = \left| \vec{E} \cdot \vec{h}_{\text{eff}}(\theta, \varphi) \right| \]

- **Phase**
  The phase of a multipath is increased by the antenna phase shift in the direction of arrival of the incoming signal.

  \[ \phi = \angle \vec{h}_{\text{eff}}(\theta, \varphi) \]

  The effective height can include the phase variation of the electric field and therefore it renders the impact of the antenna on the phase of a multipath.

- **Delay**
  At a particular frequency, the group delay is the sum of the geometric distance between the direct signal and the reflected signal, and the antenna group delay in the direction of arrival.

  \[ \vec{h}_{\text{eff f}_0 \pm \delta f} = \beta_{\pm \delta f}(\phi, \theta) \hat{u}(\phi, \theta) \]

  With \( \hat{u}(\phi, \theta) \) the unitary vector in the direction of arrival

  \[ \tau_{GD}(\phi, \theta) = -\frac{1}{2\pi} \frac{d\phi}{df} = -\frac{1}{2\pi} \frac{\angle \beta_{+\delta f}(\phi, \theta) - \angle \beta_{-\delta f}(\phi, \theta)}{2\delta f} \]

  We obtain the global group delay in the direction of arrival for the real polarization.
3. GNSS antenna models

3.2 Antenna models

• **Theoretical**
  
  We can consider the theoretical *isotropic antenna gain pattern*. This antenna model is very conservative as at low elevation the gain pattern is greater than for any realistic antenna.

• **From measurements**

  Airbus provided ENAC with gain pattern measurements on a scaled aircraft at a scaled frequency in the 3 principal planes on a 5° elevation and 5° azimuth grid. This led to an *interpolated antenna gain pattern* with a limited accuracy.

• **From electromagnetic simulations**

  We simulated using FEKO (PO and MoM) a new *simulated electric field pattern* including the complete aircraft at f and f±δf. This allows to get access to both the *antenna phase* and the *antenna group delay* at the frequency f in all direction of arrival.
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4. Importance of the antenna+aircraft far field hypothesis

- In **pedestrian** or **car** GNSS applications, the size of the vehicle is small enough to not consider its multipath effects.
- The radiating system can be reduced to the antenna as the delays induced by the vehicle are short compared to the chip period.

➢ **But** in an aeronautical application, where vehicles are of size tenth of meters, their multipath effect are more important, especially the stabilizer.

➢ **1st possible solution**: integrate the aircraft structure into the phase, delay and gain radiation pattern
4. Importance of the antenna+aircraft far field hypothesis

Simulated RH phase

L1 patch antenna mounted on aircraft

Simulated group delay

L1 patch antenna

Real wave polarization group delay (ns), patch antenna only

Real wave polarization group delay (ns), patch antenna mounted on an aircraft
4. Importance of the antenna+aircraft far field hypothesis

With 1st solution, we have modeled the radiating system antenna+aircraft as
- A far field gain radiation pattern → impact on multipath amplitude
- A phase variation pattern → impact on multipath phase
- A group delay variation pattern → impact on multipath delay

➢ But the far field limit is several kilometers away and therefore the far field assumption is not valid when there are nearby obstacles e.g. buildings.

➢ Second possible solution: consider the aircraft structure as a source of multipath and an antenna far field pattern
4. Importance of the antenna+aircraft far field hypothesis

Multipath pseudo-range errors

Observations:
- Same multipath pseudo-range error magnitude
- Same type of oscillations
- But tenth of meter of point to point difference

➢ Part of the fuselage is in the near field of the antenna radiation pattern → 3rd solution
4. Importance of the antenna+aircraft far field hypothesis

Observations:
- Solutions seem identical
- Differences decrease to several meters
- If we neglect the fuselage, both solutions work the same way
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4. Antenna far field assumption problem
5. Conclusion
Summary

• Presentation of a deterministic-statistical GNSS multipath error model
• Proposition of antenna models including phase and group delay variations
• Analysis of the aircraft structure impact on pseudo-range errors: gain oscillations at low elevation due to the fuselage, important phase disturbance at low elevation, 20 times higher group delays
• Simulation results show the importance in pseudo-range error predictions of:
  – The antenna far field limit
  – The antenna+aircraft far field limit
• The results obtained while neglecting the aircraft fuselage are good and confirm the model that include the aircraft into the radiating system.

Future works

• Study of the antenna+aircraft transfer function for all direction of arrival
• Validate simulations with the new antenna model by means of comparisons to measurements
• Then, propose a validated GNSS multipath pseudo-range error model through simulations for aircraft surface navigation
Thank you for your attention


• [Néri11]: P. Néri. Use of GNSS signals and their augmentations for Civil Aviation navigation during Approaches with Vertical Guidance and Precision Approaches, PhD thesis, Université de Toulouse, 2011


• [Ami18] C. Amielh, A. Chabory, C. Macabiau, L. Azoulai,, “Importance of the antenna model to assess multipath in airport environnements”, APS/URSI 2018, WE-UF-1.P.1, July 11th 2018