GNSS Vulnerability to Spoofing Threats and a Review of Anti-Spoofing Techniques

Ali Broumandan, Ali Jafarnia Jahromi,
Saeed Daneshmand, Gérard Lachapelle

Position, Location And Navigation (PLAN) Group
Department of Geomatics Engineering
University of Calgary

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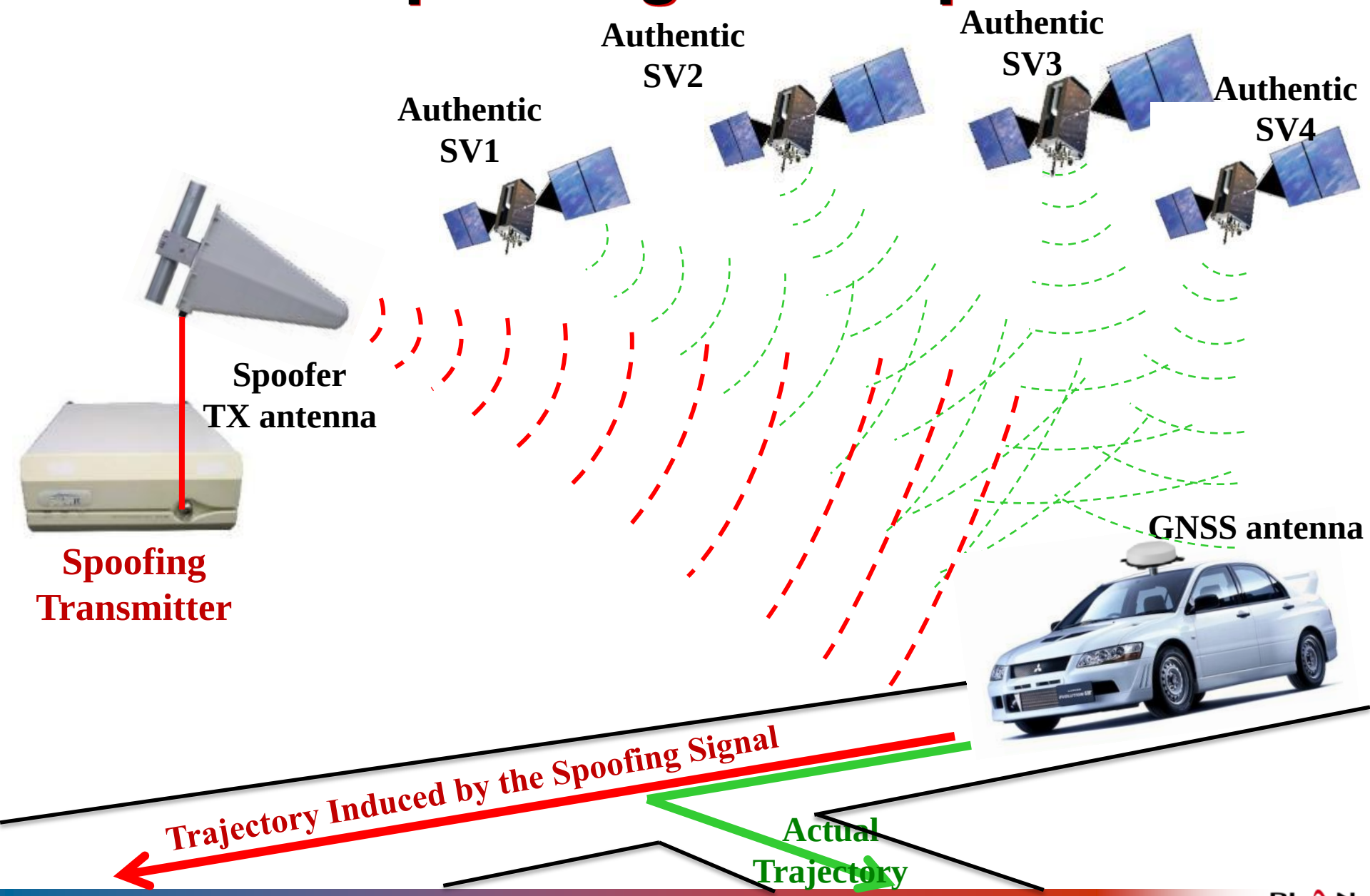
Outline

- Motivation and Background
- Spoofing and Anti-Spoofing Techniques
- Pre-Despreading Spoofing Detection
- Acquisition Level Analysis
- Tracking Level Analysis
- Position Level Authenticity Verification
- Synthetic Array Spoofing Detection
- Antenna Array Spoofing Mitigation
- Summary

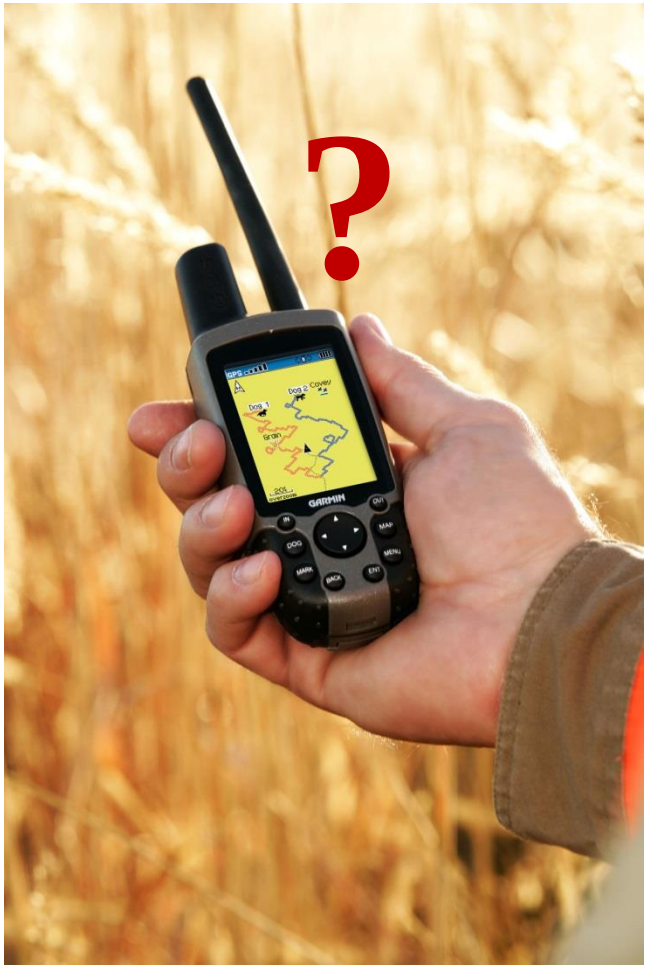
Spoofing Concept



Spoofing: A Different Type of Interference

Spoofing a deliberate interference that aims to mislead GNSS receivers into generating false PVT solution

- Spoofing signals: similar temporal and spectral characteristics to the authentic GNSS signals
- GNSS receivers are vulnerable
  - Known GNSS signal structure
  - Lack of authentication mechanism
- Spoofing is a serious threat
  - Not prohibitively costly
  - Significant motivations for spoofing due to wide-spread GNSS applications
  - Receiver is not aware of being spoofed (it is providing a PVT solution)



GPS Spoofing Headlight

- Mainstream make announcement on the vulnerability of GNSS to spoofing attack
- $80 million yacht hijacked
- Spoofing drone and UAS
- Vulnerability of timing systems

Vulnerability of Unmanned Vehicles to GPS Spoofing Attack

- Unmanned Aircraft Systems (UAS) and drones
- US congress has mandated the Security of Transportation to accelerate safety of civil unmanned aircraft systems
- Amazon is working on a new delivery system to get packages into customers' hands within 30 min using UAS

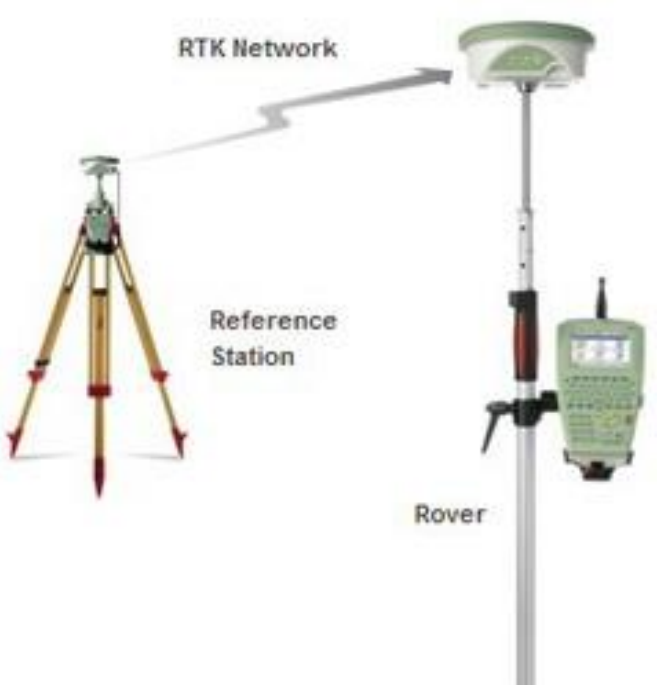
Vulnerability of Timing Systems to Spoofing Attack

- The Power Grid's Vulnerability to GPS Spoofing Attack
- Telecommunication links are using GPS time synchronization
- Stock Market time synchronization is mostly depend on civilian GPS

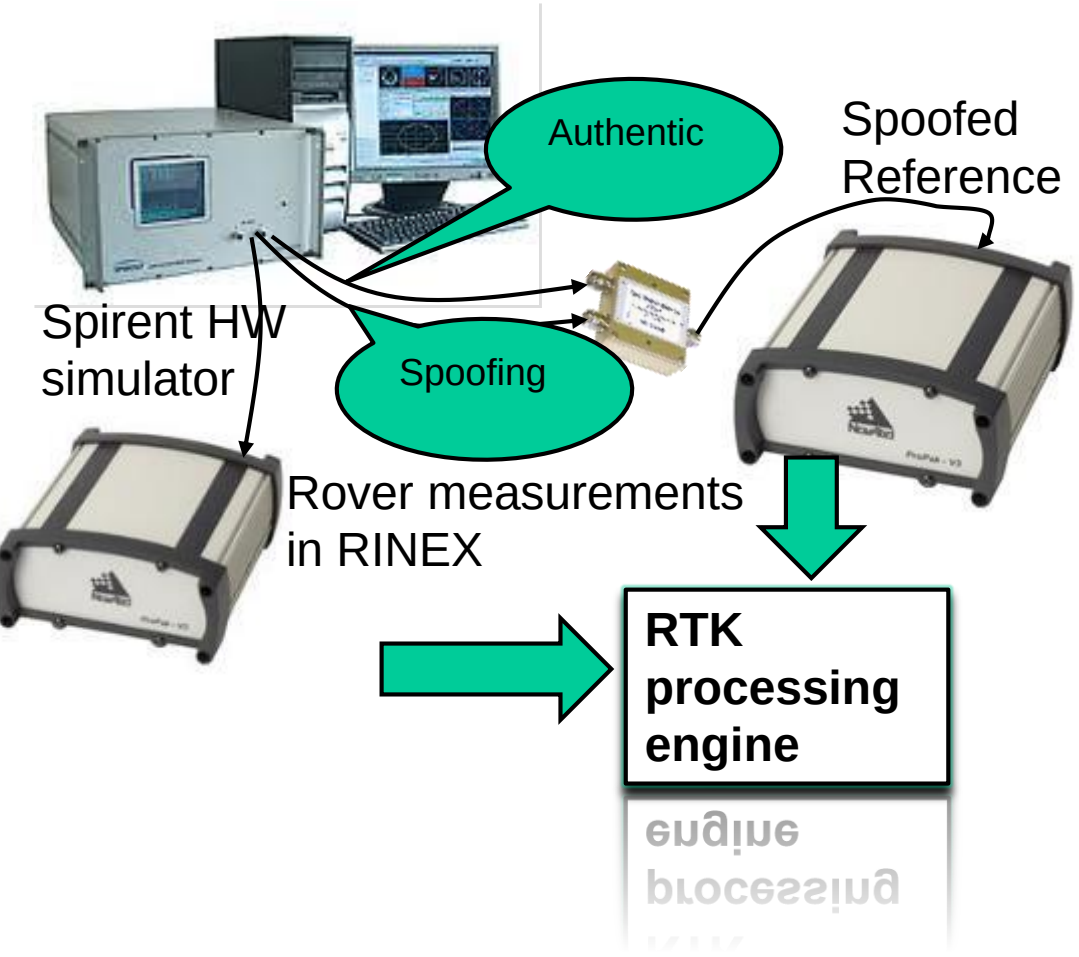
http://gpsworld.com/wirelessinfrastructuregoing-against-time-13278/

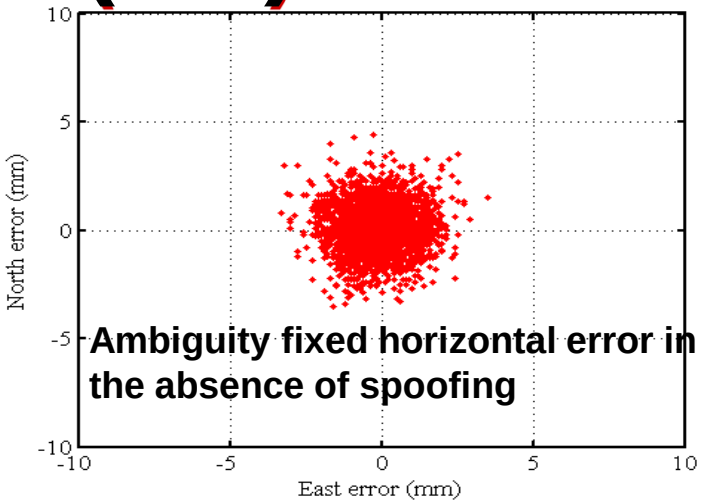
Vulnerability of RTK Application to Spoofing Attack (I/II)

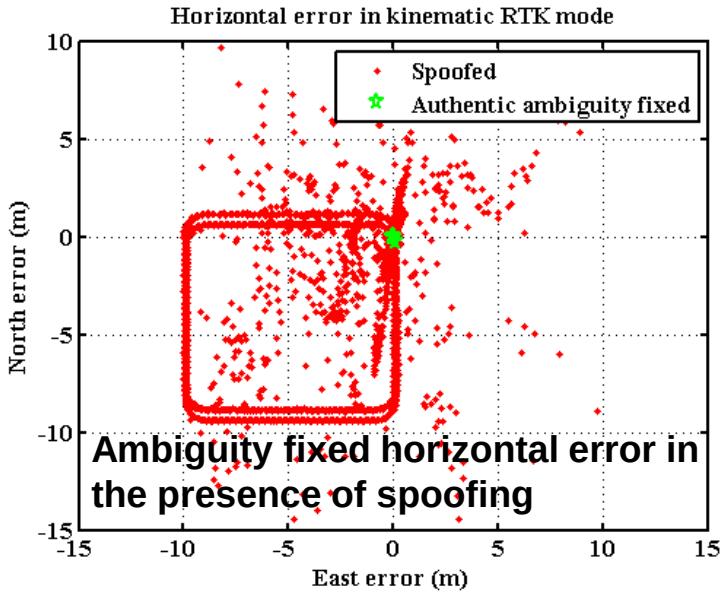
- RTK base stations are highly vulnerable to the spoofing attack
- What does to a rover position solution if the base station is spoofed?
- A two-channel hardware simulator and two NovAtel receivers in reference-rover scenario have been used to asses the spoofing vulnerability
- A spoofing attack is simulated for a RTK application where the spoofed horizontal trajectory of the base station is spoofed by 10 m



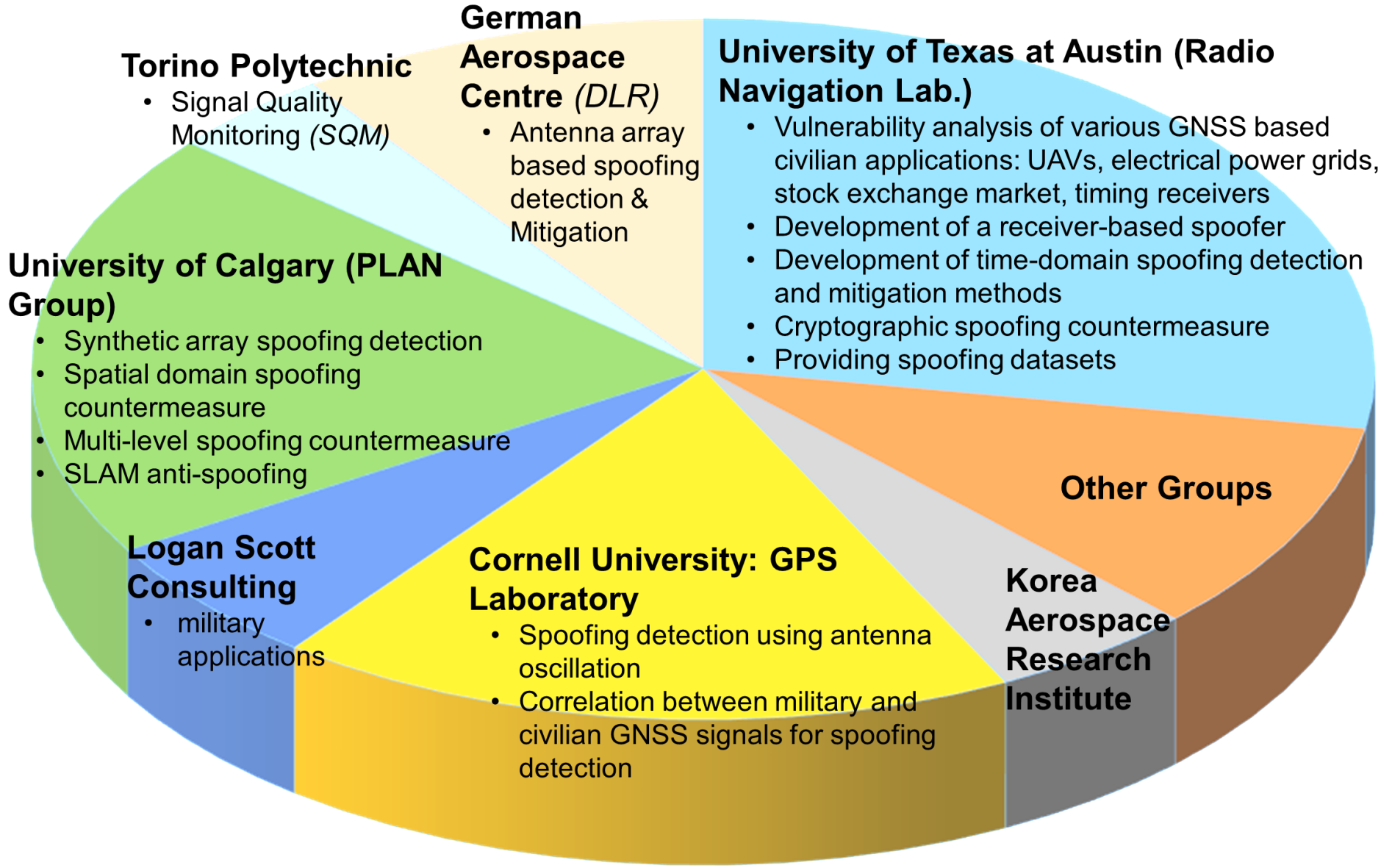
Vulnerability of RTK Application to Spoofing Attack (II/II)







Some Research Groups



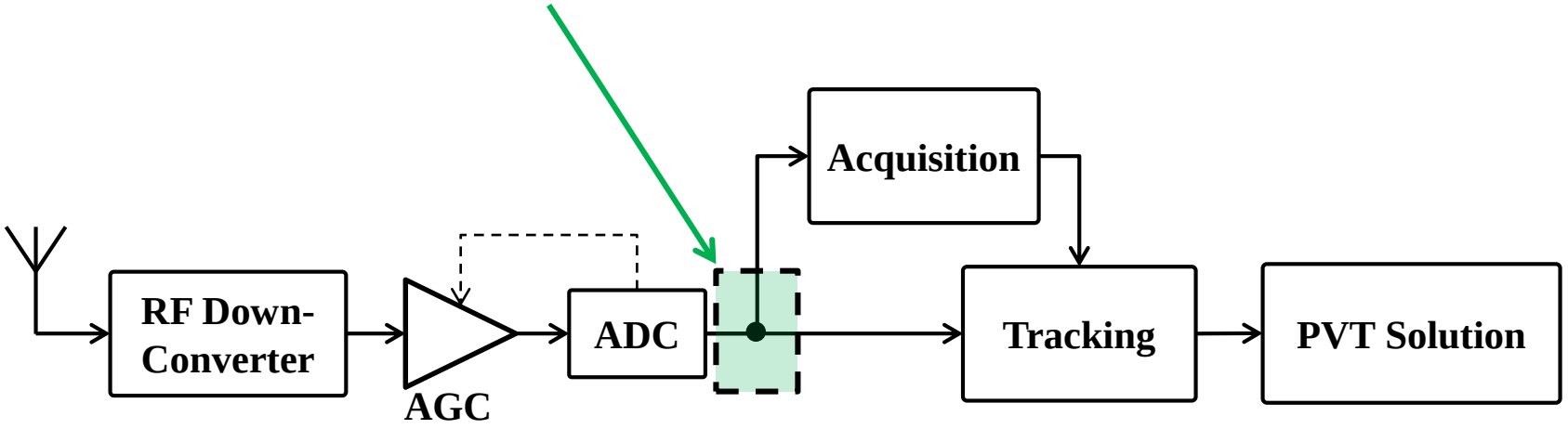
Spoofing Generation Categories

- **GPS signal generator**
  - Simplest spoofing technique but still very effective
- **Receiver based spoofer**
  - Spoofer is coupled to a GPS receiver
  - Hard to detect compared to GPS signal generator
  - Self jamming avoidance is an important issue
- **Advanced receiver based spoofer**
  - A receiver-spoofer with multiple antennas
  - Very hard to detect even for AOA estimator receivers
  - Very expensive and complex
  - Many practical implementation issues

Spoofing Countermeasure Methods

Positioning	**Receiver Autonomous Integrity Monitoring (RAIM)**	Integrity Check among Different Pseudorange Measurements
	Consistency Cross Check with Other Navigation Systems	Cross check with IMU solutions, Cross check with cellular and Wi-Fi positioning solutions
Data bit	**Time of Arrival (TOA) Methods**	Monitoring the bit transition boundaries
	Navigation Message Analysis	Consistency check among satellites navigation messages
Signal Processing	**Correlation Peak Monitoring**	Signal Quality Monitoring (SQM), Monitoring the distribution of correlation peak.
	Spatial Discrimination of Spoofing Signals	Antenna Array Processing, Synthetic Antenna Arrays
	Power Based Methods	C/N_0 Monitoring, Absolute Power Monitoring, L1/L2 Power level Comparison, …

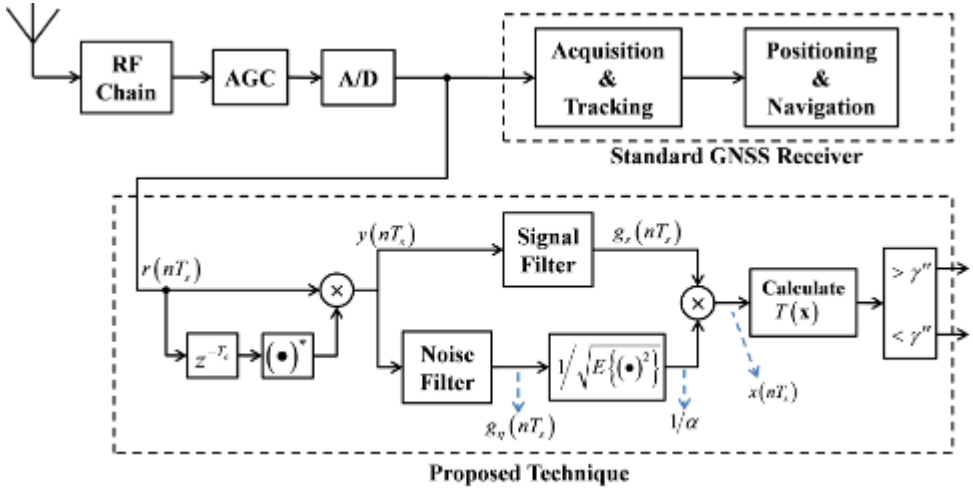
Pre-Despreading Analysis

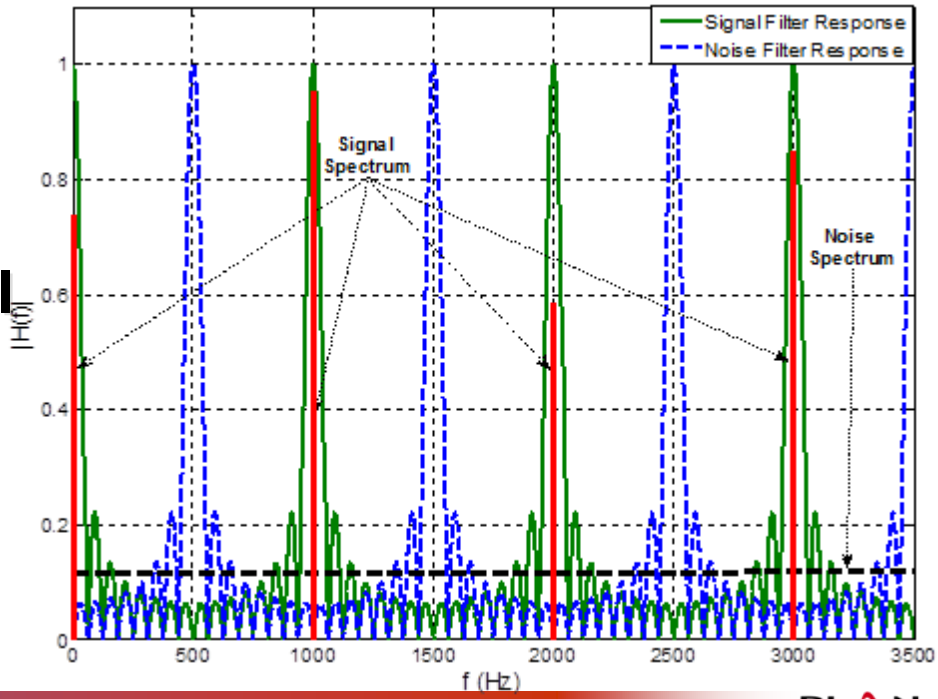


- Jafarnia-Jahromi, A., A. Broumandan, J. Nielsen and G. Lachapelle (2014) Pre-Despreading Authenticity Verification for GPS L1 C/A Signals. Navigation, Journal of The Institute of Navigation, in press.

Pre-Despreading Spoofing Detection

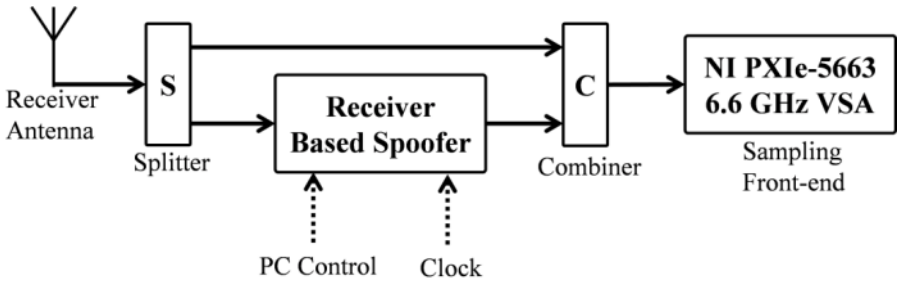
- Looking for abnormal power content of cyclo-stationary signals
- GPS L1 C/A
  - Line spectrum 1KHz spacing
  - Delay and Multiply (DAM)
- Processing method
  - Differential Doppler removal
  - Noise comb filtering
  - Signal comb filtering
  - Signal normalization
  - Spoofing detection

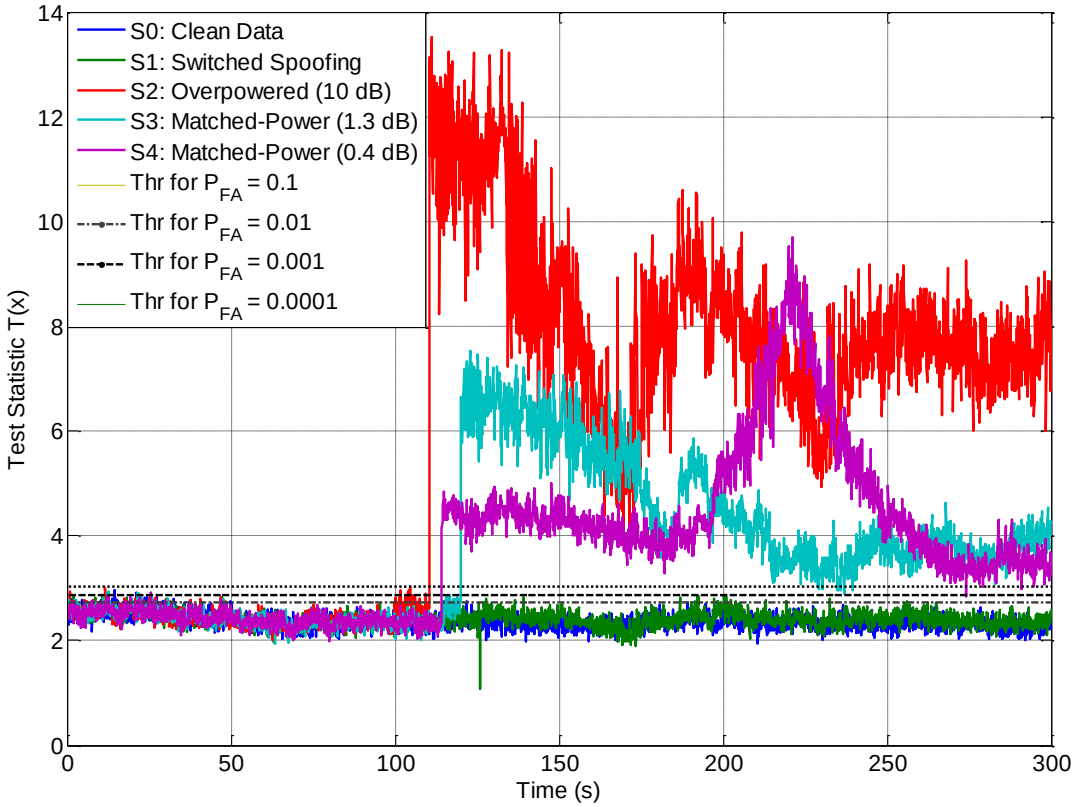




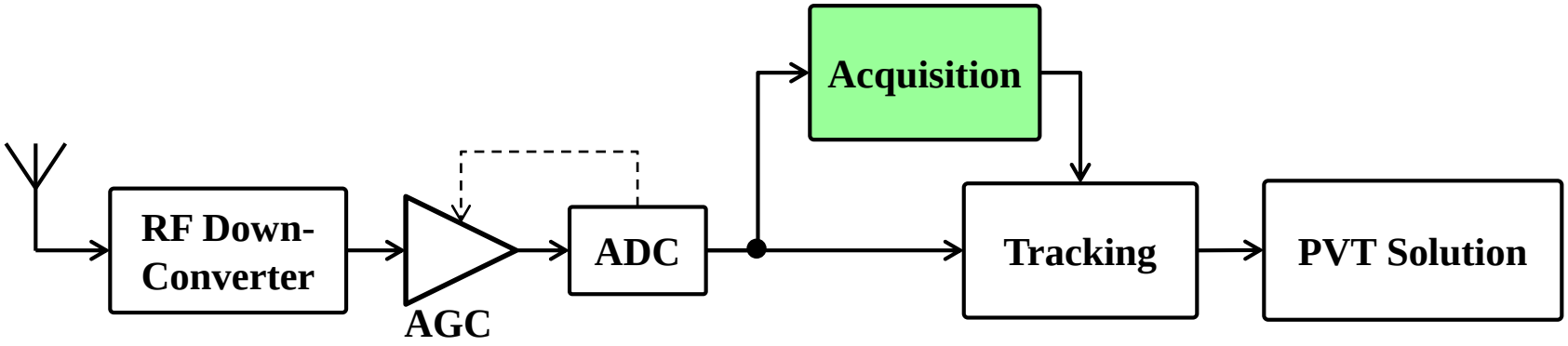
TEXBAT Data Processing

- **Spoofing datasets provided by RNL at Texas University at Austin**
- **Static spoofing scenarios**
  - **S1: Switched attack**
  - **S2: Overpowered** *(10 dB advantage)*
  - **S3: Matched Power** *(1.3 dB advantage)*
  - **S4: Matched Power** *(0.4 dB advantage)*
- **Spoofing starts after 100 s**





Acquisition Level Analysis



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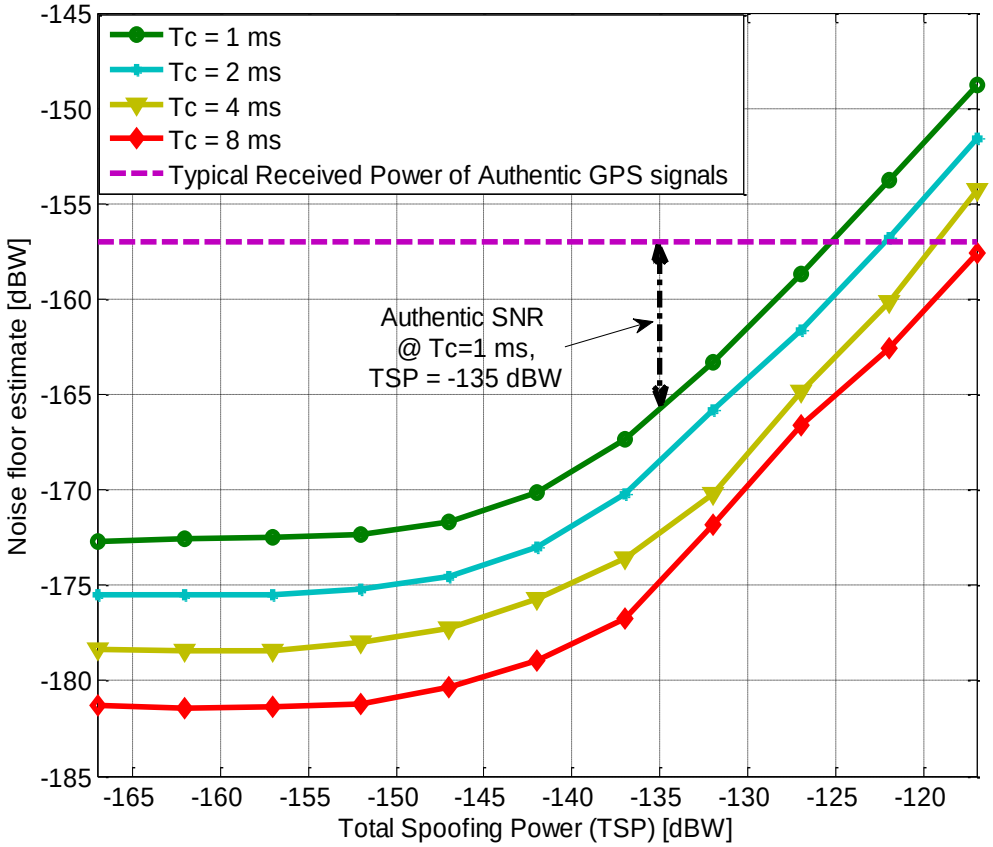
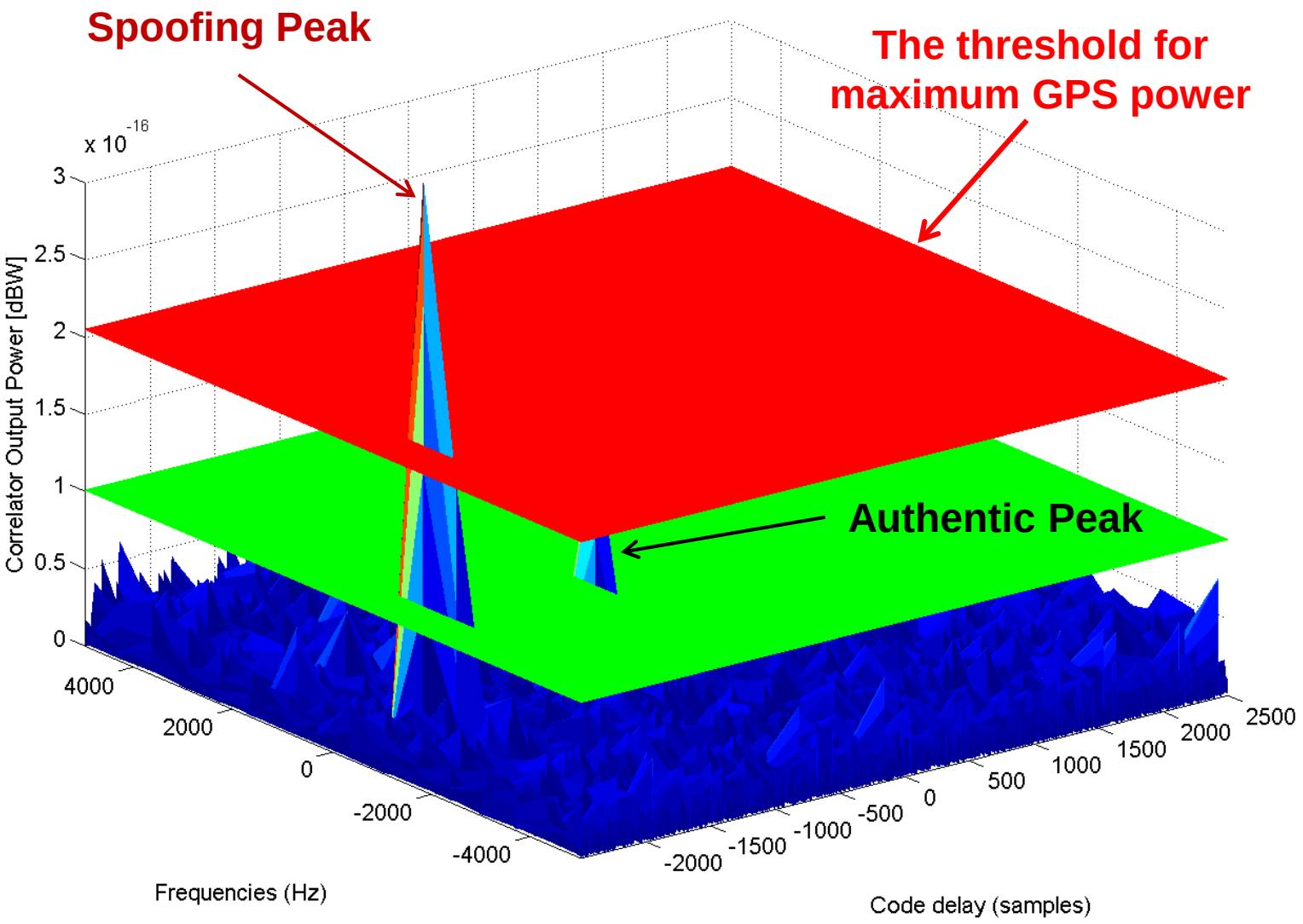
Acquisition Vulnerability to Spoofing

- Additional fake correlation peaks
  - Potentially misdirects the acquired PRN set, code delay and Doppler estimate
- Receiver noise floor increase
  - Generated by the cross correlation between spoofing PRNs and local replicas
  - Spoofing acts as a wide-band interference
  - Affects all the PRNs

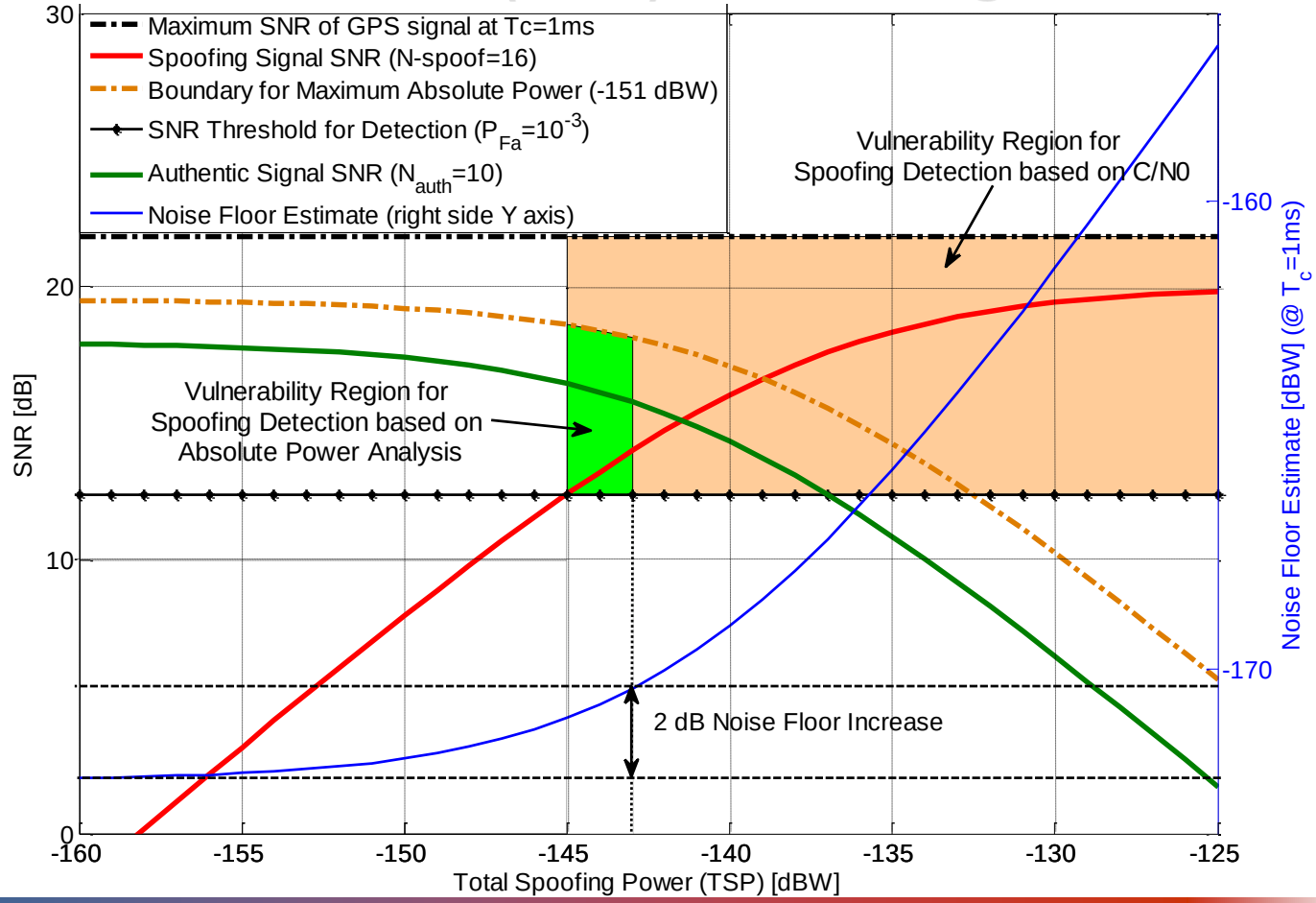


Multiple Thresholds in CAF

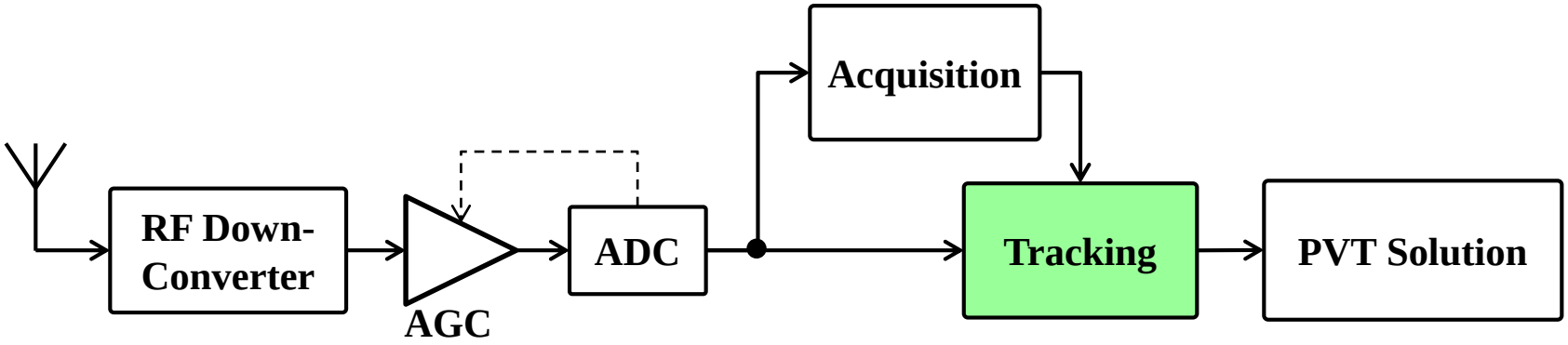


SNR vs. Absolute Power Monitoring

- **Absolute power monitoring**
  - **Signal level monitoring, Noise level monitoring**
- **Signal to Noise Ratio (SNR) monitoring**



Tracking Level Analysis



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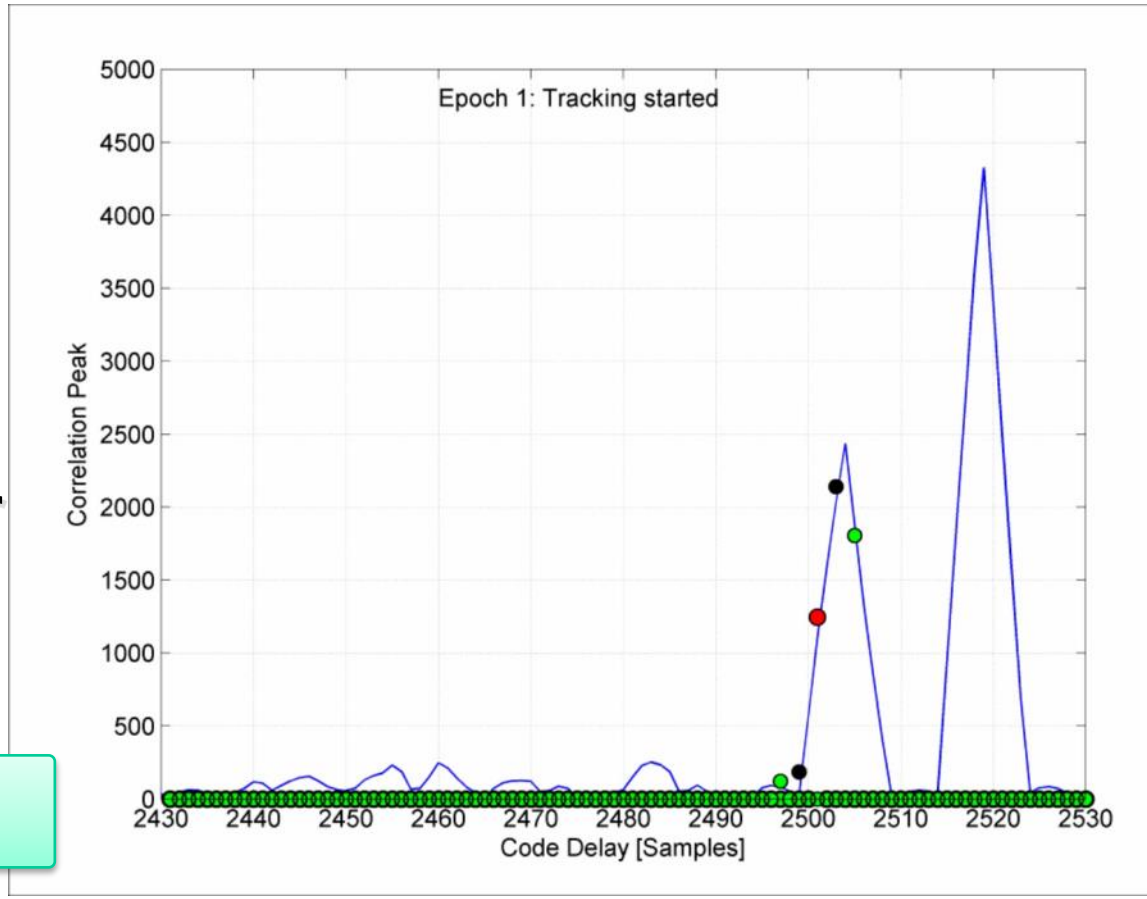
Spoofing Attack on Tracking Receivers

- **Tracking receiver**
  - **Focused on tracking authentic correlation peaks**
  - **Less vulnerable to non-aligned spoofing peaks**
- **Spoofer lifts-off the tracking point of the receiver**
- **Two categories:**
  - **Consistent Doppler**

$$\Delta f_l^{a,s}[k] = -f_{RF}\,\Delta\dot{\tau}_l^{a,s}[k]$$

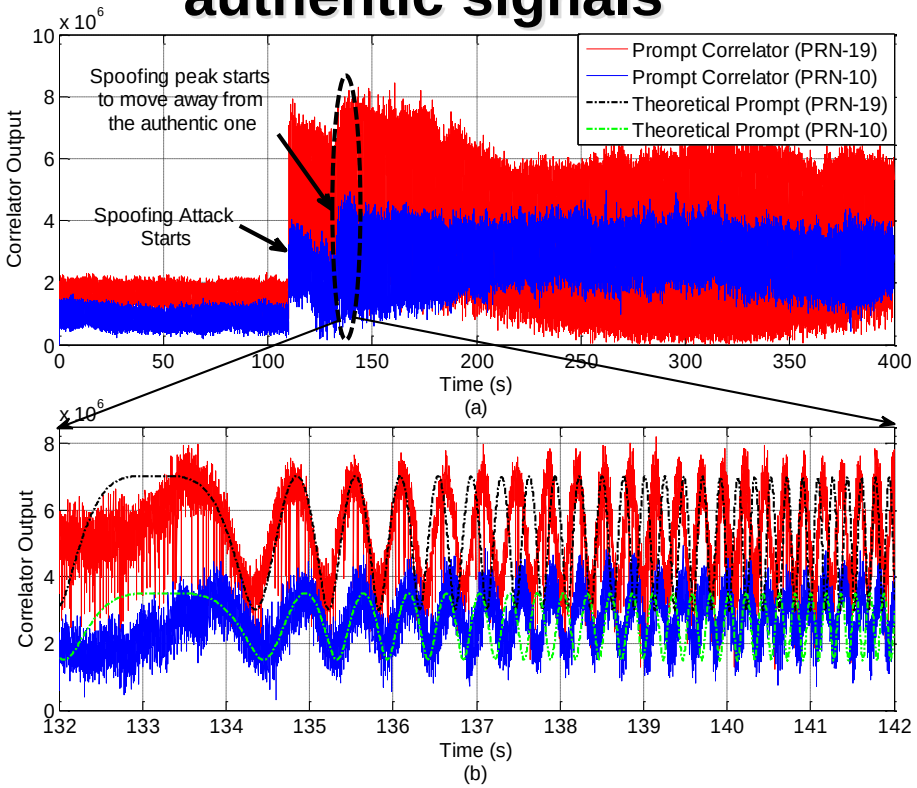
  - **Locked Doppler**

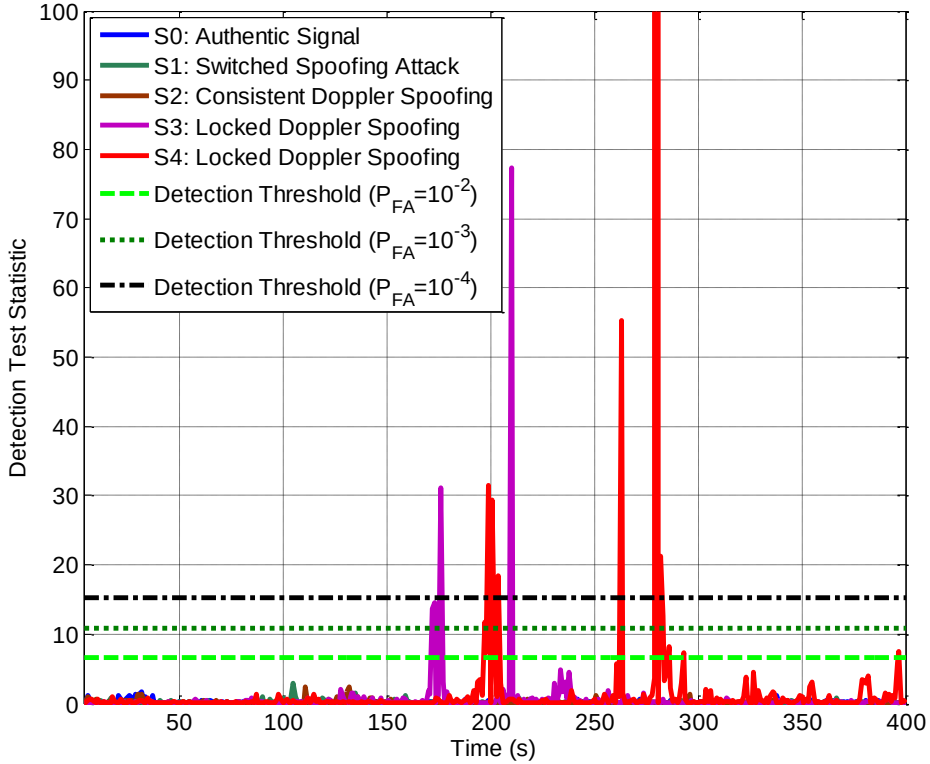
$$\Delta f_l^{a,s}[k] = 0 \rightarrow \Delta\varphi_l^{a,s}[k] = \Delta\phi_{l,0}^{a,s}$$



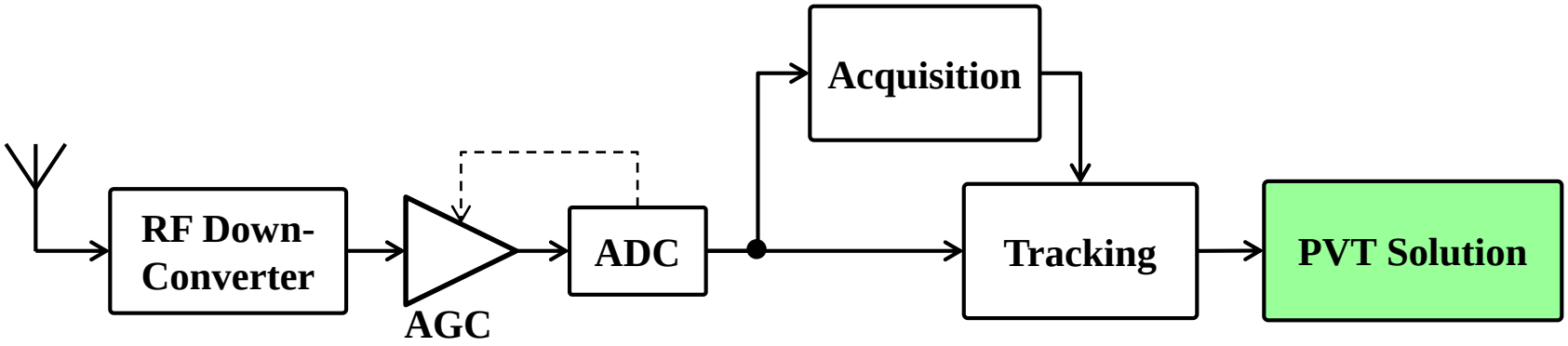
Spoofing Countermeasure during Tracking

- **Consistent Doppler:**
  - Amplitude fluctuations due to the interaction between spoofing and authentic signals
- **Locked Doppler:**
  - Consistency check between PLL and DLL loop filter outputs





Position Level Analysis



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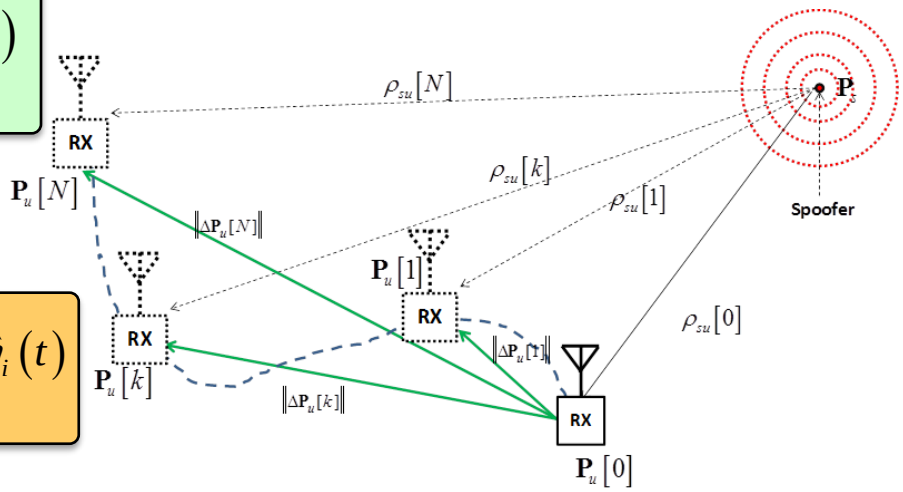
Position Level Authenticity Verification

- **Authentic pseudorange**

$$PR_i(t) = \underbrace{\rho_i(t)}_{\text{Specific to } PRN_i} + cdt_i(t) + \underbrace{c\,dT_u(t)}_{x(t)\text{: Common among all PRNs}} + \eta_i(t)$$

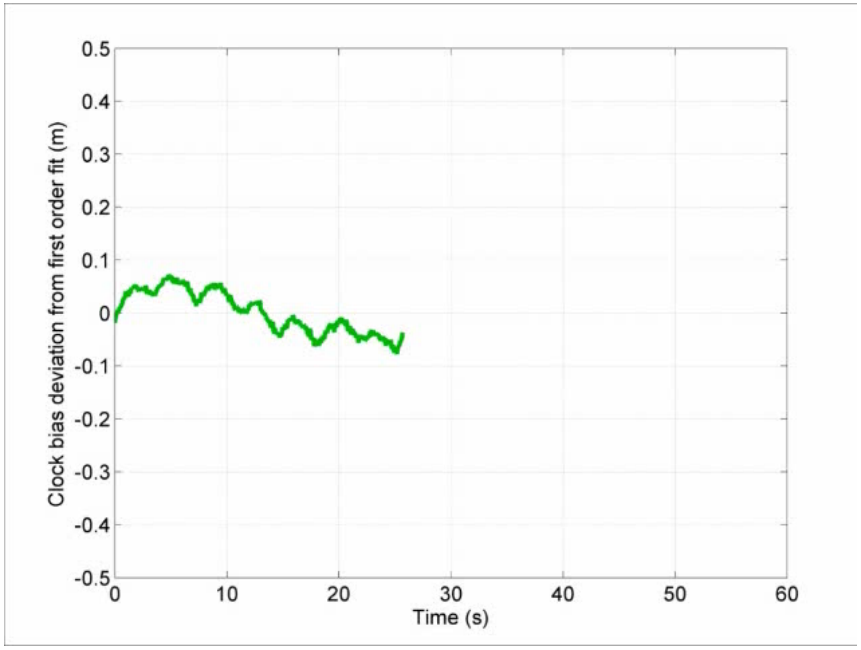
- **Spoofed pseudorange**

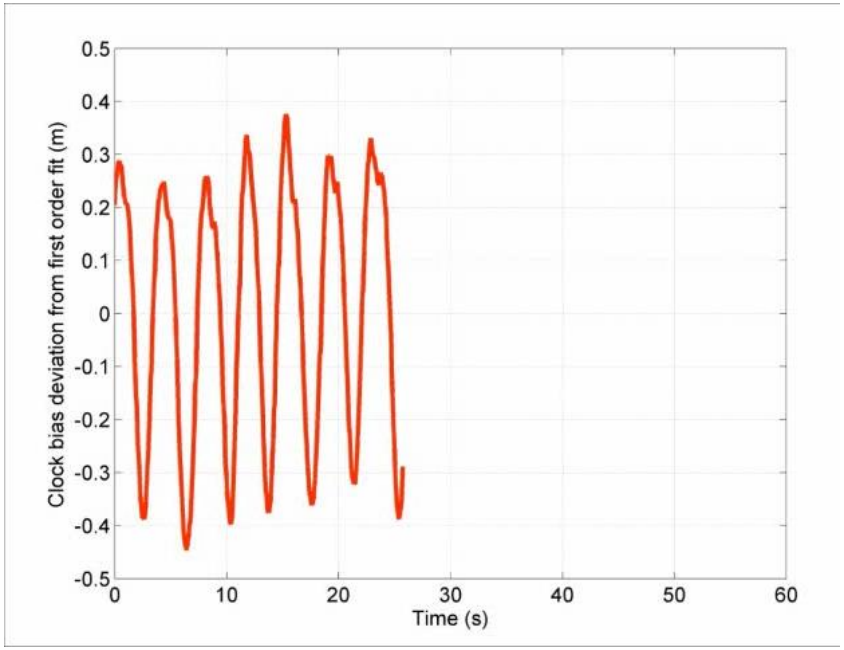
$$\hat{PR}_i(t) = \underbrace{\hat{\rho}_i(t) + cd\hat{t}_i(t)}_{\text{Specific to } PRN_i} + \underbrace{c\,dT_u(t) + \rho_{su}(t) - c.dT_s(t)}_{\hat{x}(t)\text{: Common among all PRNs}} + \hat{\eta}_i(t)$$



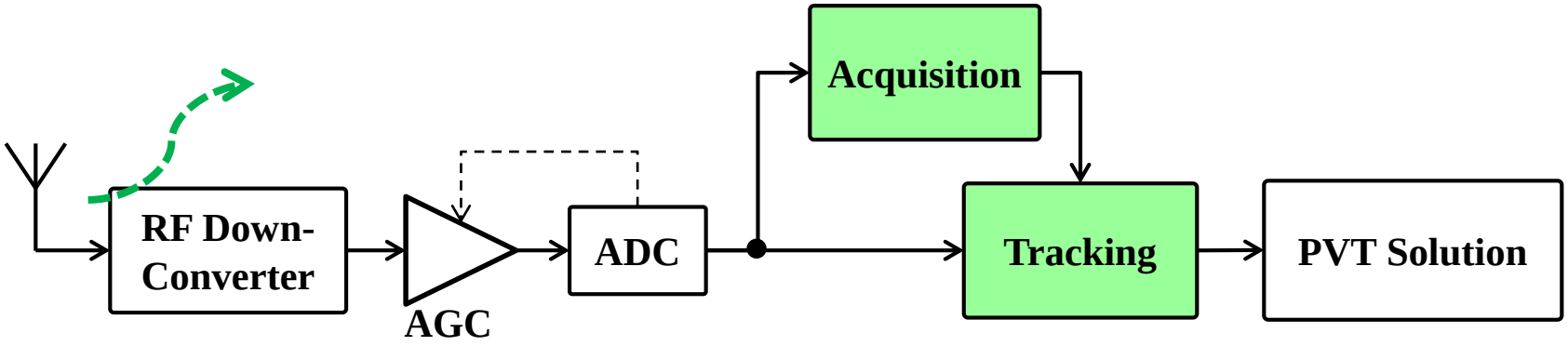
- **Spoofing Detection (the idea)**
  - Receiver motion causes pseudorange variation
  - All spoofing PRNs coming from the same source
  - Common spoofer-user range (ρ_{su}) variation
  - Clock state will be affected for a spoofed PVT solution

Handheld Circular Motion





Synthetic Array Processing



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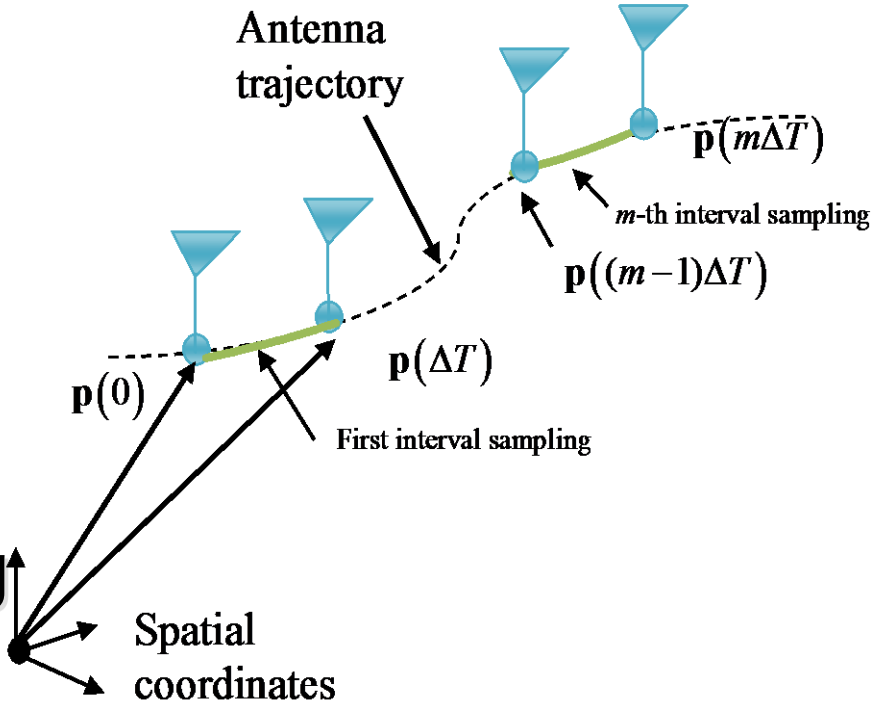
- Nielsen, J., A. Broumandan and G. Lachapelle (2011) GNSS Spoofing Detection for Single Antenna Handheld Receivers. NAVIGATION, 58, 4, 335-344.

Synthetic Array Processing

- **Spatial correlation coefficient is a metric to discriminate spoofing**
- **The processing interval is divided into *M* subintervals**
- $A_i^A(\mathbf{p}(t),t)$ **and** $A_i^S(\mathbf{p}(t),t)$ **are assumed constant during each subinterval**
- **The detection problem can be developed as**

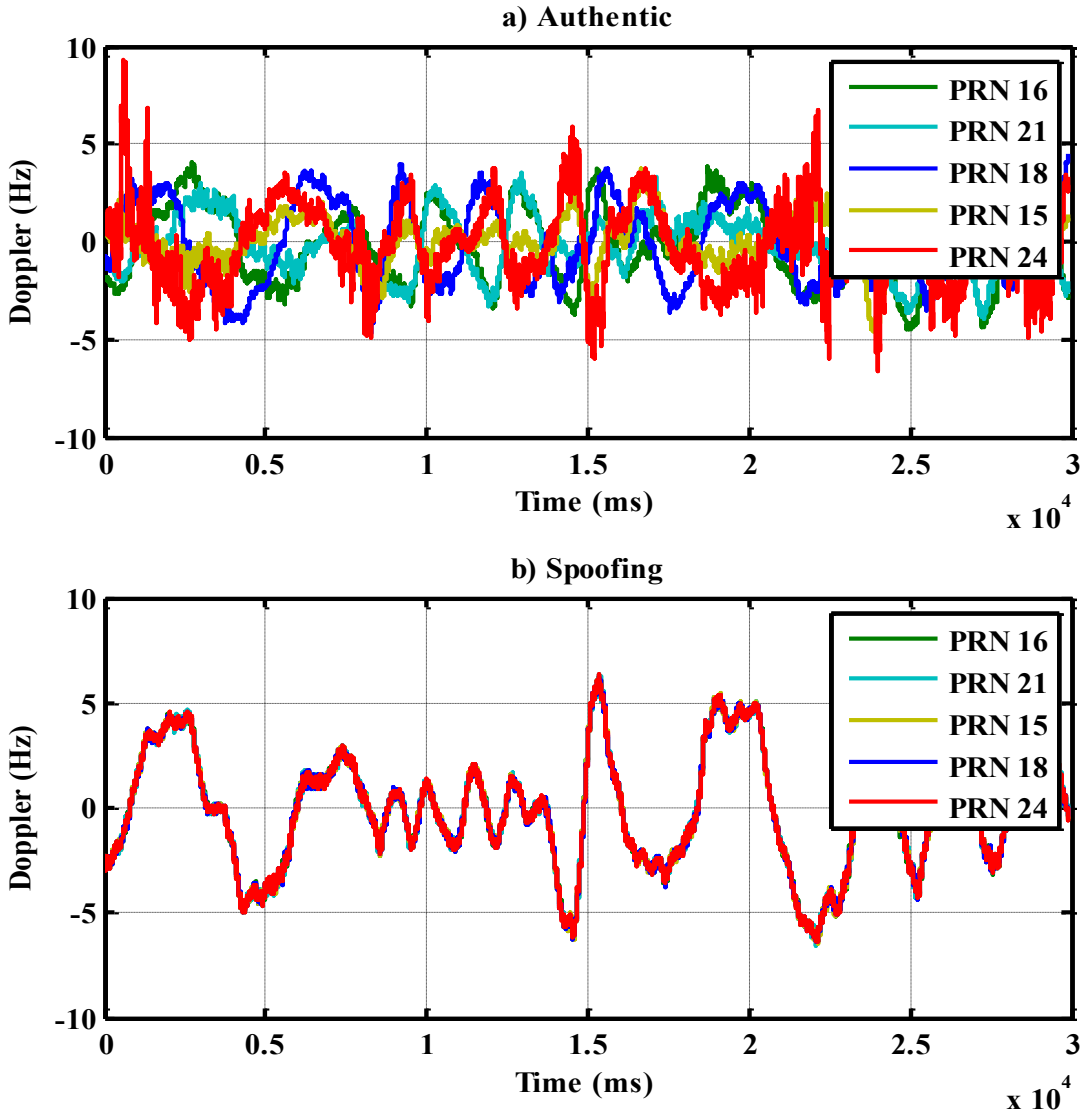


$$\mathbf{x}_i = \begin{cases} \mathbf{a}_i^S \times \boldsymbol{\alpha}_i^S + \boldsymbol{\eta}_i^S = \boldsymbol{\Lambda}_i^S + \boldsymbol{\eta}_i^S & H_1 \\ \mathbf{a}_i^A \times \boldsymbol{\alpha}_i^A + \boldsymbol{\eta}_i^A = \boldsymbol{\Lambda}_i^A + \boldsymbol{\eta}_i^A & H_0 \end{cases}$$

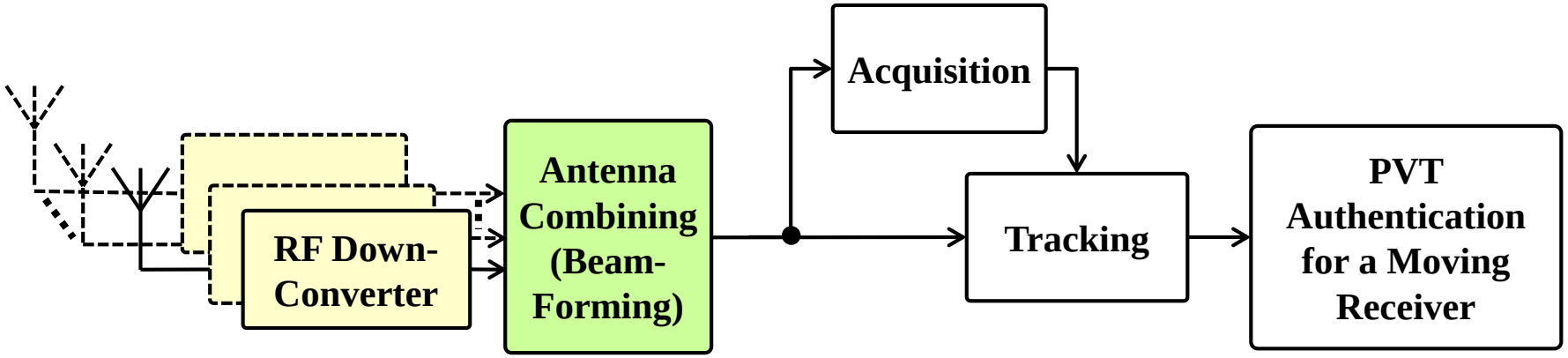
$$\rho_{ij} = \frac{E\left[\mathbf{x}_i \mathbf{x}_j^H\right]}{\sqrt{E\left[\mathbf{x}_i \mathbf{x}_i^H\right]}\sqrt{E\left[\mathbf{x}_j \mathbf{x}_j^H\right]}}.$$

Spoofing Discrimination based on Doppler Pairwise Correlation

- Measured Doppler due to the antenna motion for the authentic and spoofing signals
- Authentic Doppler values are uncorrelated while the spoofed ones are correlated



Antenna Array Processing



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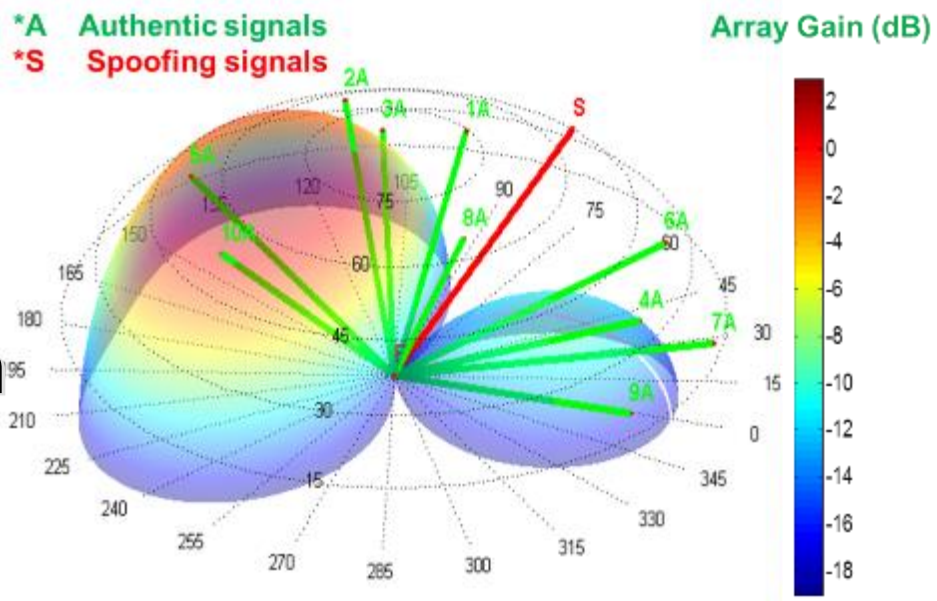
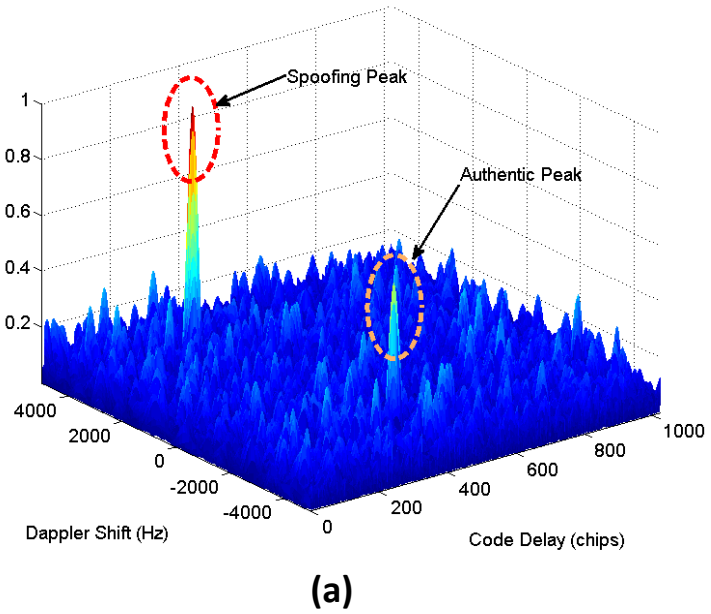
Antenna Array Processing

- **Each Signal has Specific Spatial Signature Vector (SSV)**
- **Spoofer spatial detection**
  - **Authentic signals**
    - ✓ **Different SSVs**
  - **Spoofing signals**
    - ✓ **All PRNs coming from the same source**
    - ✓ **The same SSV**
- **Spoofing mitigation**
  - **Spatial filtering (Null Steering)**



Nullifying Spoofing Signals

- Real-time operation
- Low computational complexity
- Pre-despreading operation
- Applicable for both civilian and military signals
- Array antenna considerations
  - No need for array calibration
  - Small antenna separation



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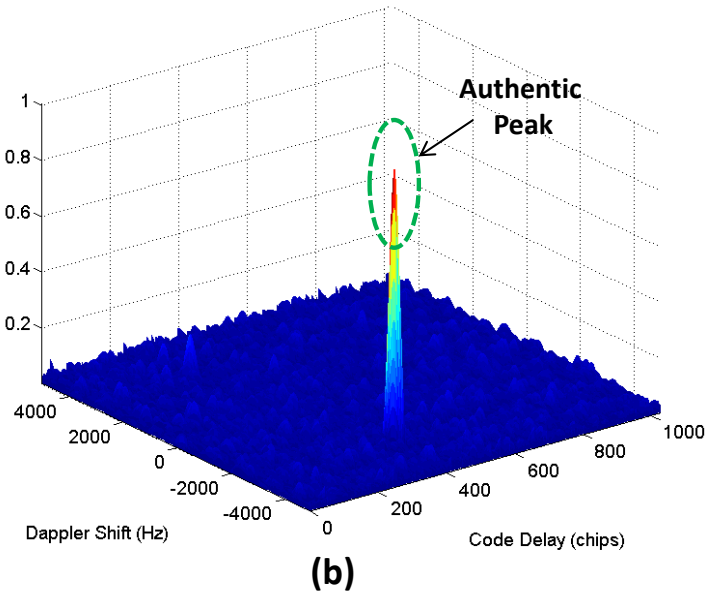
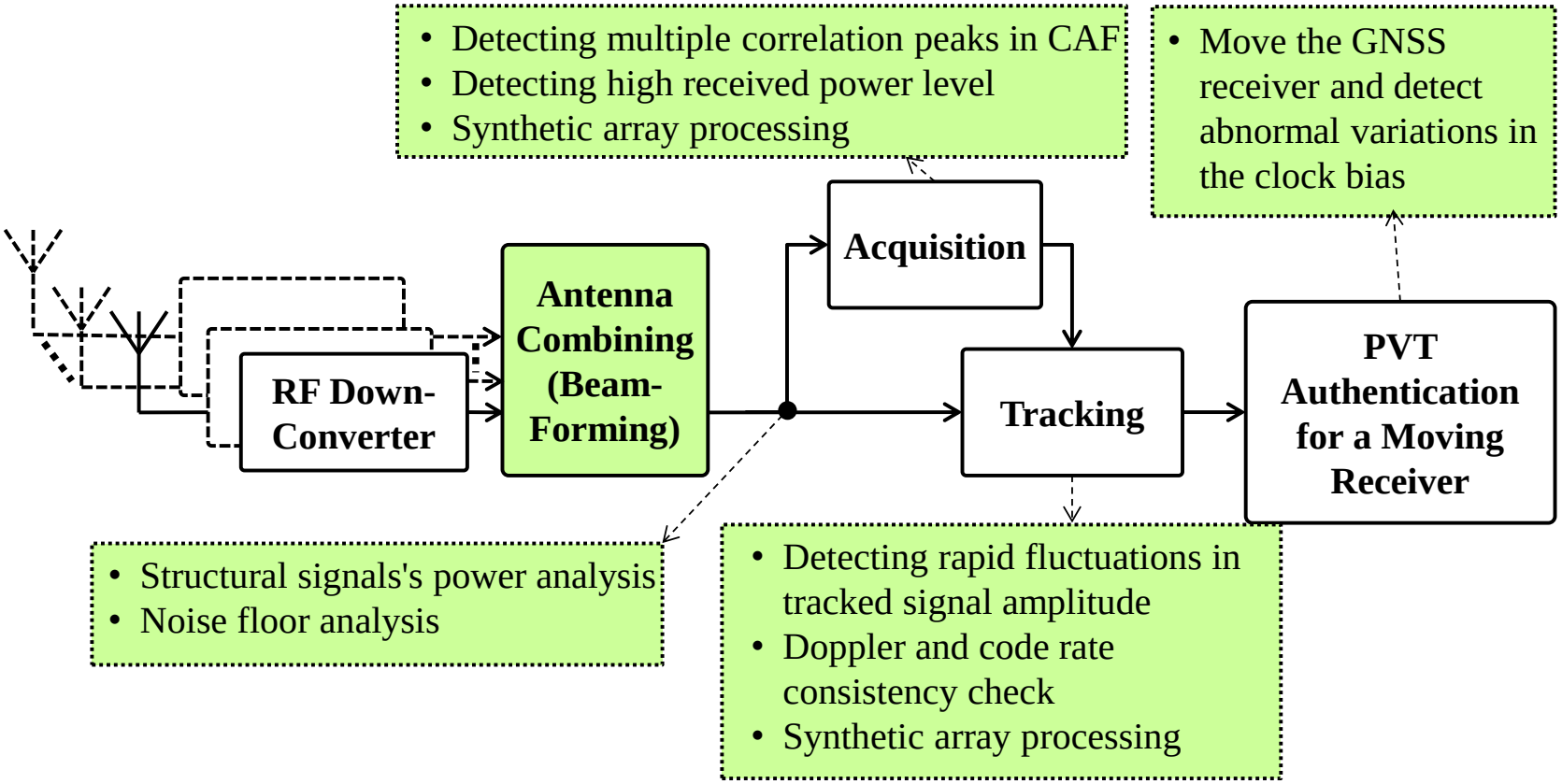


(b)

Summary

- **A possible structure of a stand-alone anti-spoofing GNSS receiver**
- **Increased resistance against spoofing signals**



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