Cornell University

GNSS Spoofing Detection using Two-Antenna Differential Carrier Phase

Mark L. Psiaki

Sibley School of Mech. & Aero. Engr., Cornell Univ.

Brady W. O'Hanlon & Steven P. Powell

School of Electrical & Computer Engr., Cornell Univ.

Jahshan A. Bhatti, Kyle D. Wesson, & Todd E. Humphreys

Aero. Engr. & Engr. Mechanics, UT/Austin

Andrew Schofield

Sea ID, Master of the White Rose of Drachs

ION/GNSS+ 2014, 12 Sept. 2014

Acknowledgements

- The owner of the White Rose of Drachs lent his yacht to support the testing reported here

- The White Rose crew aided this project in many ways

Motivation:

- Detect attack by Humphreys-class spoofer on civilian GPS receiver or meaconing attack on a military receiver

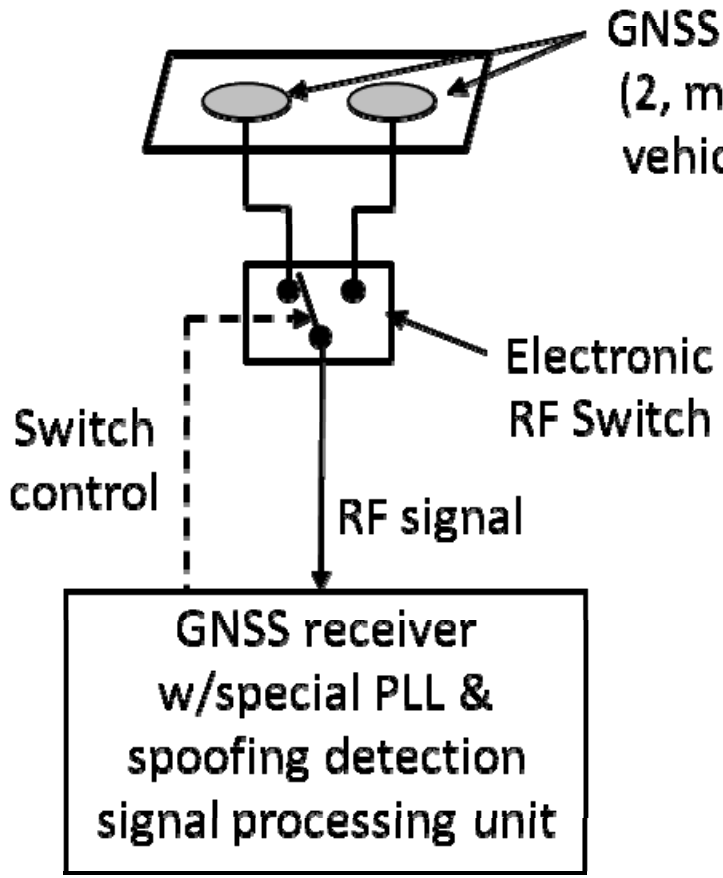
Strategy:

- Exploit differences of signal arrival geometry between non-spoofed case & spoofing from a single transmitter using CDGPS/attitude-determination principles
- Develop detection statistic based on difference of fits to spoofed & non-spoofed models of single-differenced carrier-phase between 2 antennas
- Implement real-time version
- Test detection system against live-signal spoofing attacks on a superyacht during a cruise around Italy

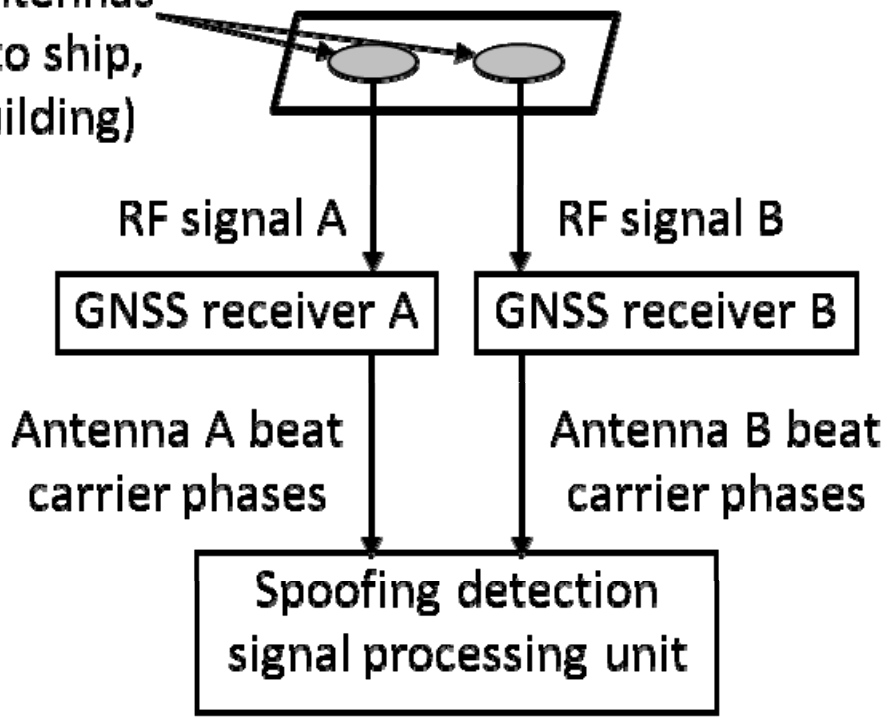
Outline

I. Spoofing detection system architecture
II. Non-spoofed & spoofed carrier phase models
III. Detection tests with maximum likelihood optimal estimation of unknown attitude parameters
IV. Live-signal spoofing attack experiments aboard a yacht
V. Results, analyses, & discussion
VI. Summary & conclusions
VII. Future plans

Two Configurations of a 2-Antenna GNSS Spoofing Detection System

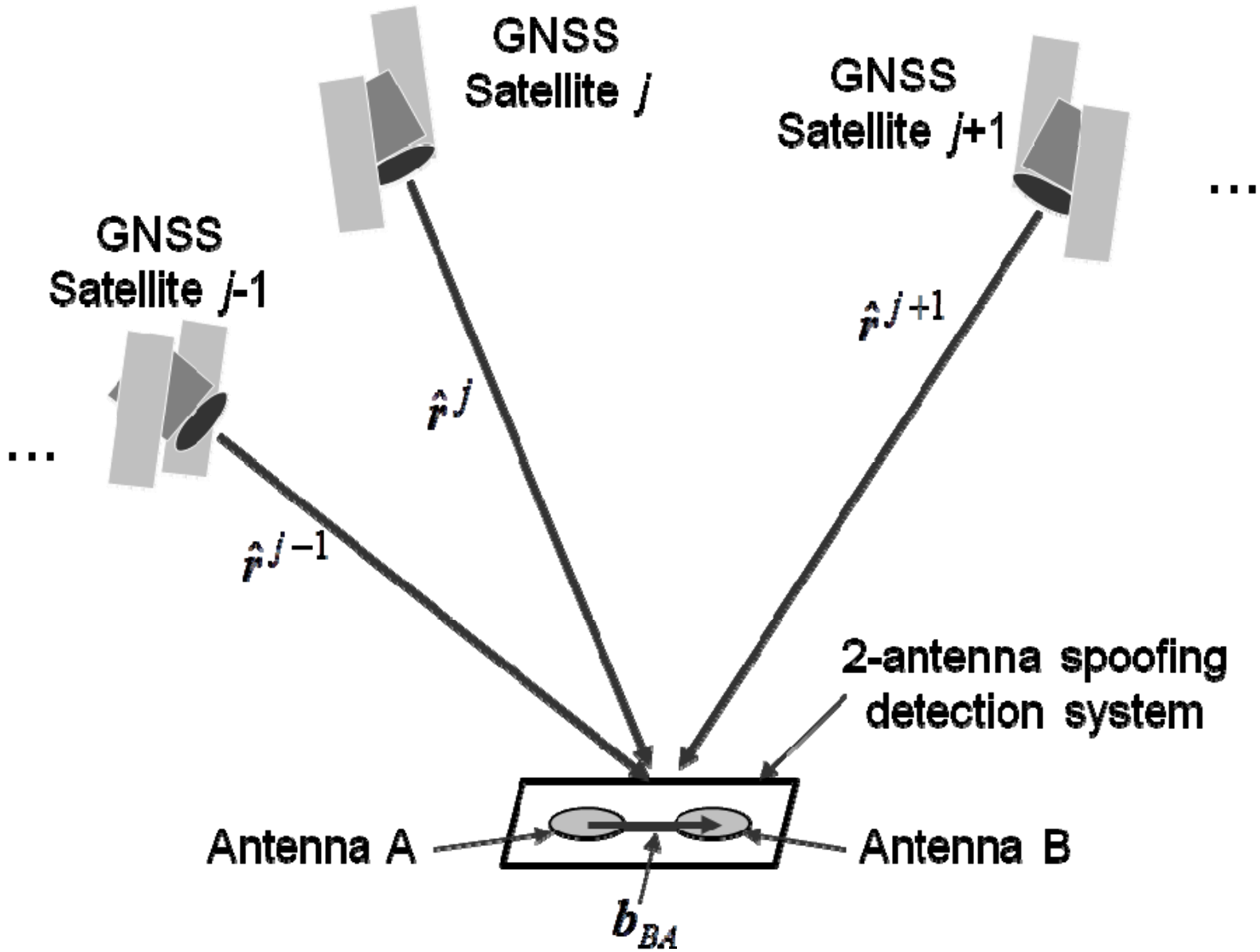


RF-switched-signal/single-receiver configuration

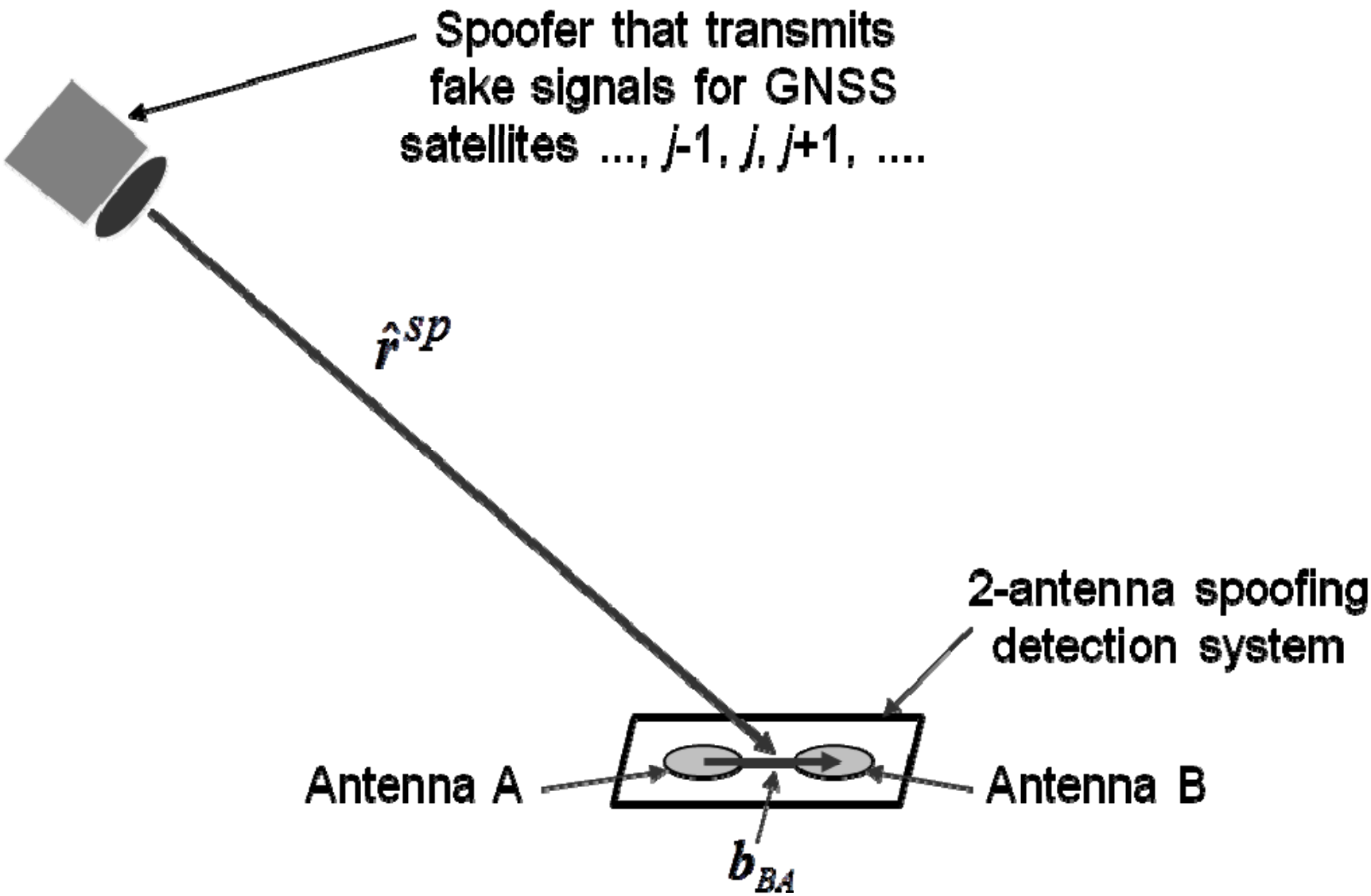


Two-receiver configuration

Geometry of Non-Spoofed Case



Geometry of Single-Transmitter Spoofed Case



Carrier Phase Models

- Non-spoofed case

$$\Delta\phi_{BA}^{j} = \phi_{B}^{j} - \phi_{A}^{j}$$

$$= -\frac{2\pi}{\lambda}(\hat{\boldsymbol{r}}^{j})^{\mathrm{T}} A^{\mathrm{T}} \boldsymbol{b}_{BA} + \beta + 2\pi\Delta N_{BA}^{j} + n_{mpBA}^{j} + n_{rcvrBA}^{j}$$

$$= -\frac{2\pi\rho_{BA}}{\lambda}(\hat{\boldsymbol{r}}^{j})^{\mathrm{T}} \hat{\boldsymbol{r}}_{BA} + \beta + 2\pi\Delta N_{BA}^{j} + n_{mpBA}^{j} + n_{rcvrBA}^{j}$$

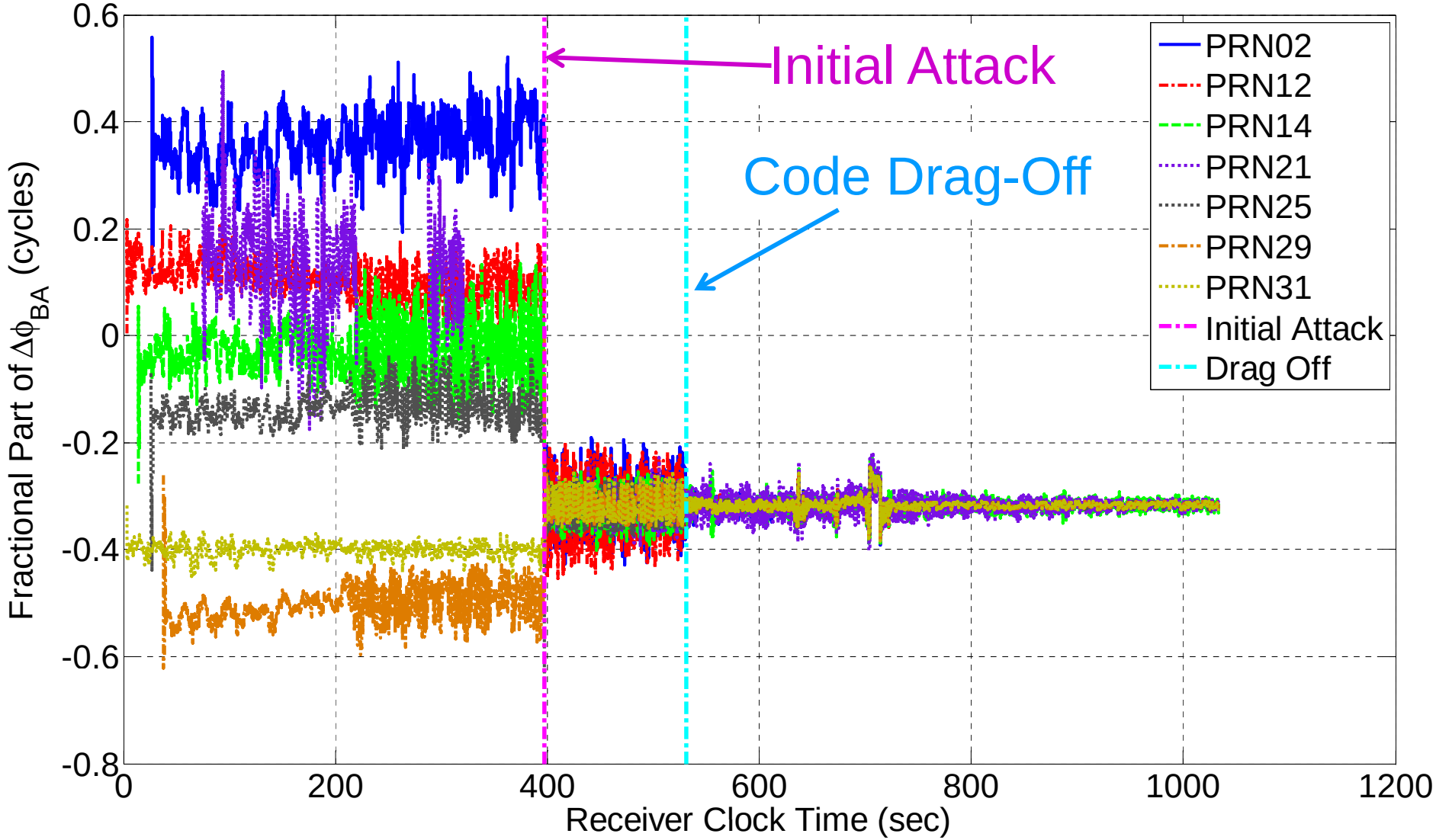
- Spoofed case

$$\Delta\phi_{BA}^{j} = -\frac{2\pi\rho_{BA}}{\lambda}(\hat{\boldsymbol{r}}^{sp})^{\mathrm{T}} \hat{\boldsymbol{r}}_{BA} + \beta + 2\pi\Delta N_{BA}^{j} + n_{mpBA}^{sp} + n_{rcvrBA}^{j}$$

$$= \beta_{sp} + 2\pi\Delta N_{BA}^{j} + n_{rcvrBA}^{j}$$

with $\beta_{sp} = -\frac{2\pi\rho_{BA}}{\lambda}(\hat{\boldsymbol{r}}^{sp})^{\mathrm{T}} \hat{\boldsymbol{r}}_{BA} + \beta + n_{mpBA}^{sp}$

Single-Differenced Carrier Phase Responses to Spoofing Attack



Hypothesis Test Statistic

- Non-spoofed case antenna baseline estimation

find: $\hat{\boldsymbol{r}}_a, \beta, \Delta N_{BA}^1, \ldots, \Delta N_{BA}^L$

to minimize: $J_{nonsp}(\hat{\boldsymbol{r}}_{BA}, \beta, \Delta N_{BA}^1, \ldots, \Delta N_{BA}^L) =$

$$\frac{1}{2}\sum_{j=1}^{L} \frac{[\Delta\phi_{BA}^j + \frac{2\pi\rho_{BA}}{\lambda}(\hat{\boldsymbol{r}}^j)^{\mathrm{T}}\hat{\boldsymbol{r}}_{BA} - \beta - 2\pi\Delta N_{BA}^j]^2}{(\sigma_{rcvr}^j)^2 + \sigma_{mp}^2}$$

subject to: $(\hat{\boldsymbol{r}}_a)^{\mathrm{T}}\hat{\boldsymbol{r}}_a = 1,\ \Delta N_{BA}^1 = 0,\ \Delta N_{BA}^j$ integer-valued for $j = 2, \ldots, N$

- Spoofed case bias/ambiguity estimation

find: $\beta_{sp}, \Delta N_{BA}^1, \ldots, \Delta N_{BA}^L$

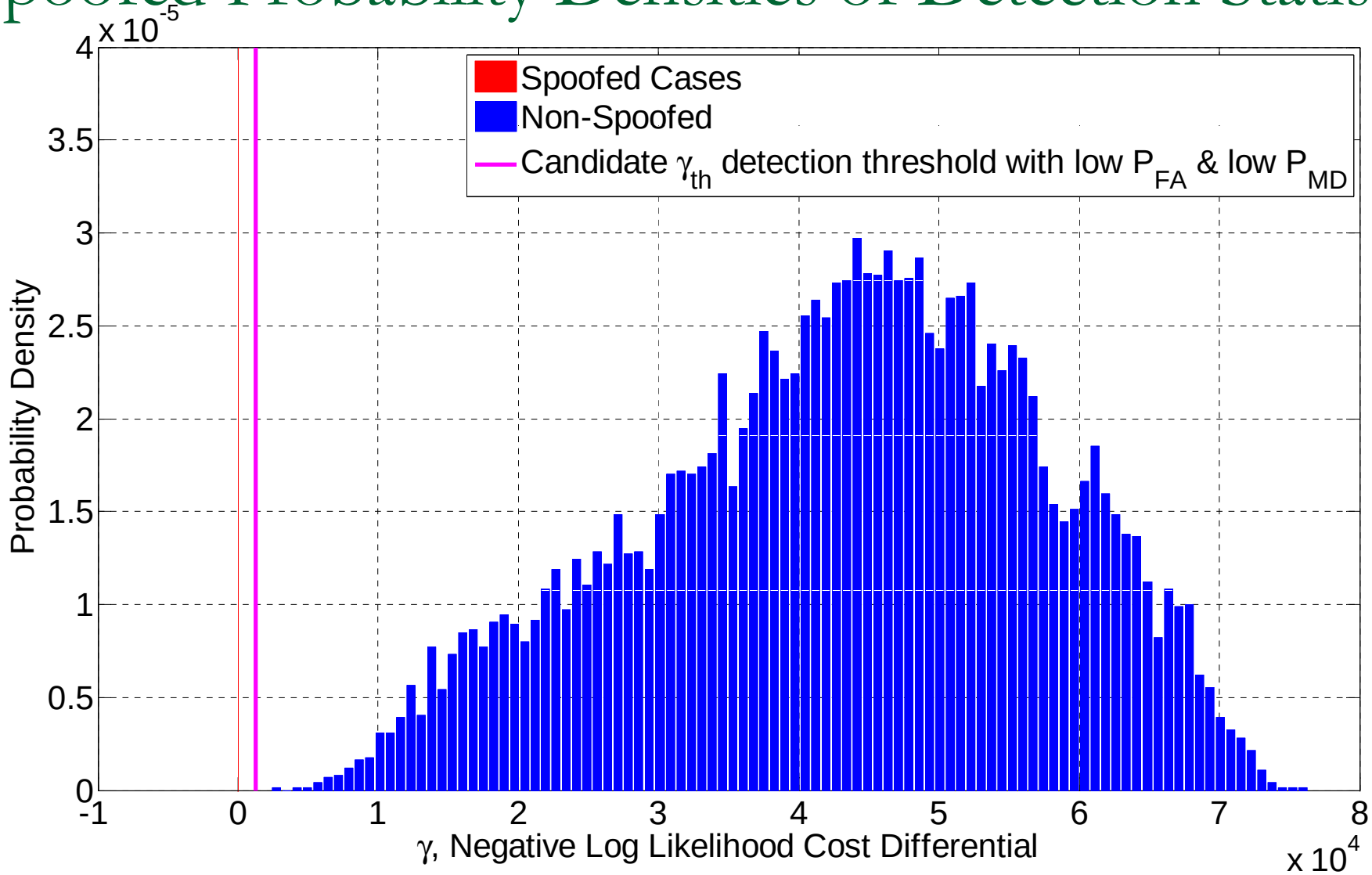
to minimize: $J_{sp}(\beta_{sp}, \Delta N_{BA}^1, \ldots, \Delta N_{BA}^L) = \frac{1}{2}\sum_{j=1}^{L} \frac{[\Delta\phi_{BA}^j - \beta_{sp} - 2\pi\Delta N_{BA}^j]^2}{(\sigma_{rcvr}^j)^2}$

subject to: $\Delta N_{BA}^1 = 0,\ \Delta N_{BA}^j$ integer-valued for $j = 2, \ldots, N$

- Difference-of-fits spoofing detection test statistic

$$\gamma = J_{sp}(\beta_{spopt}, \Delta N_{BAspopt}^1, \ldots, \Delta N_{BAspopt}^L)$$
$$- J_{nonsp}(\hat{\boldsymbol{r}}_{BAopt}, \beta_{opt}, \Delta N_{BAnsopt}^1, \ldots, \Delta N_{BAnsopt}^L)$$

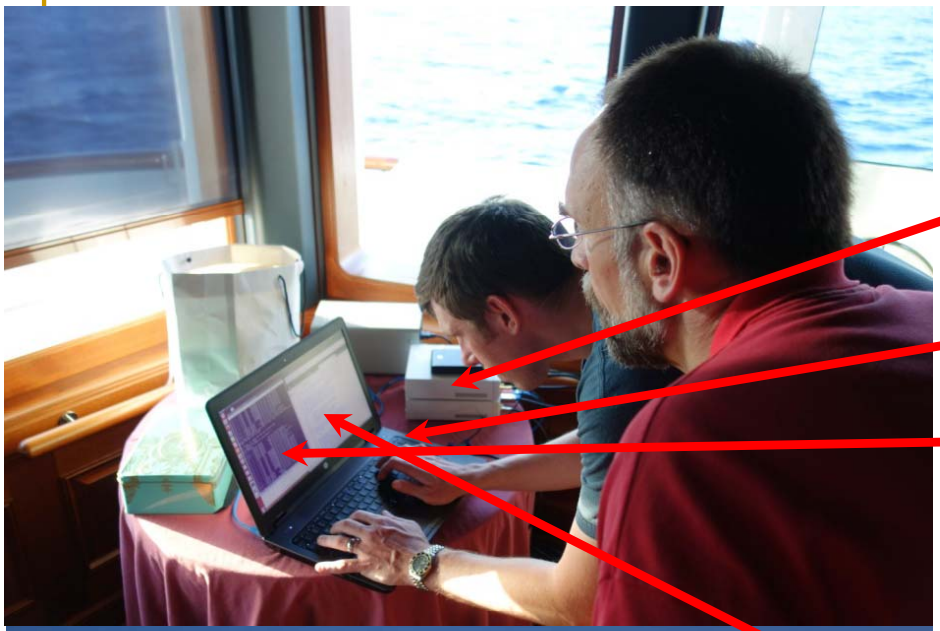
Monte-Carlo Simulation of Spoofed & Non-Spoofed Probability Densities of Detection Statistic



Antenna Separation = 14 cm, 7 satellites, GDOP: 2.4, C/N_0: 34.12 to 49.7 dB-Hz

The Texas Lying Machine, Would-be Hijacker of the White Rose

Prototype Lie Detector, White Rose Defender

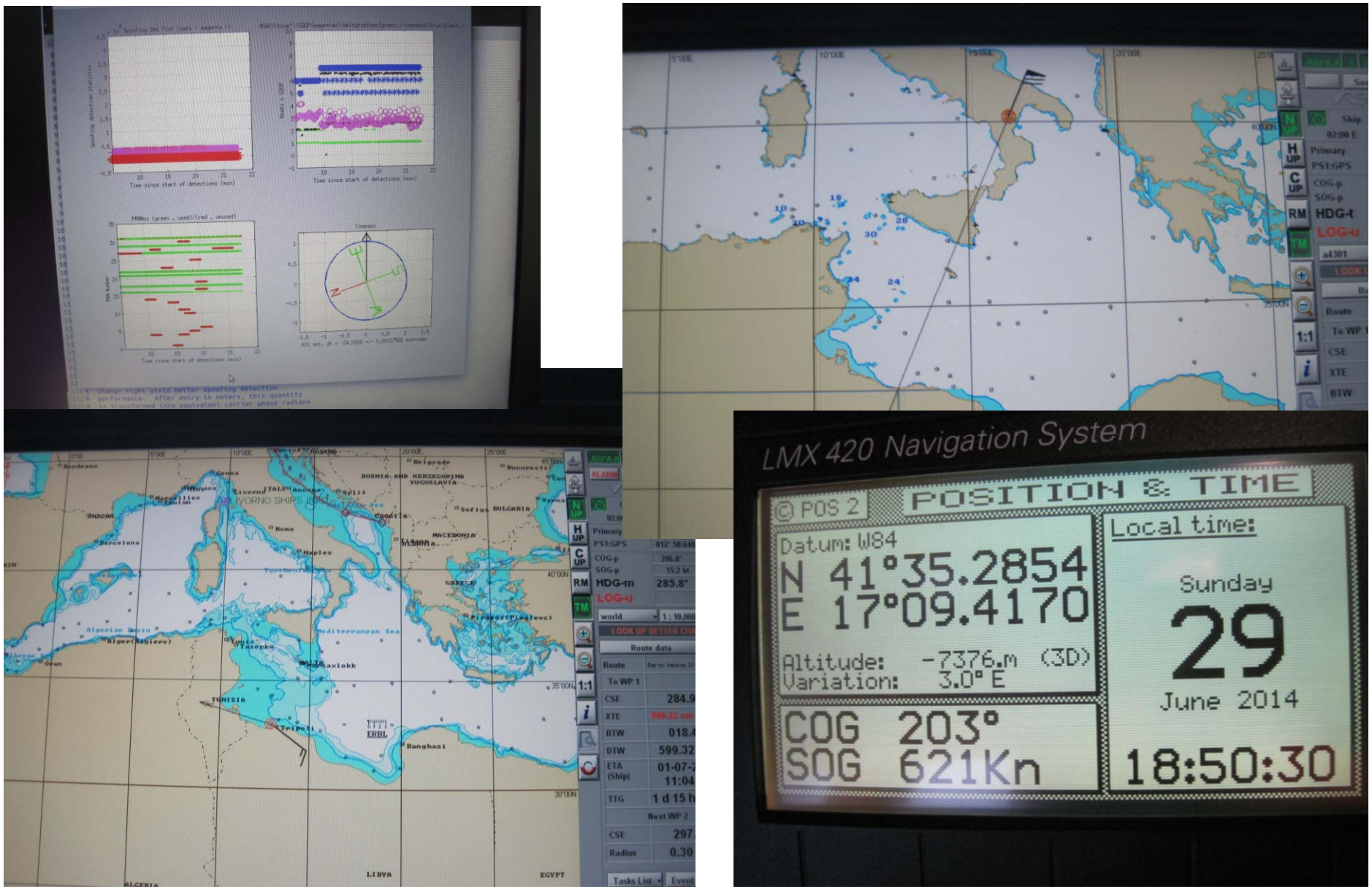


- Receiver:
  - 2 USRPs
  - 1 laptop running 2 parallel UTAustin/Cornell real-time software receivers on 2 live USRP data streams
- Spoofing detector:
  - Matlab-based detection & graphical output tic function
  - Called by real-time C receiver code & fed $\Delta\phi_{BA}^{j}$ values

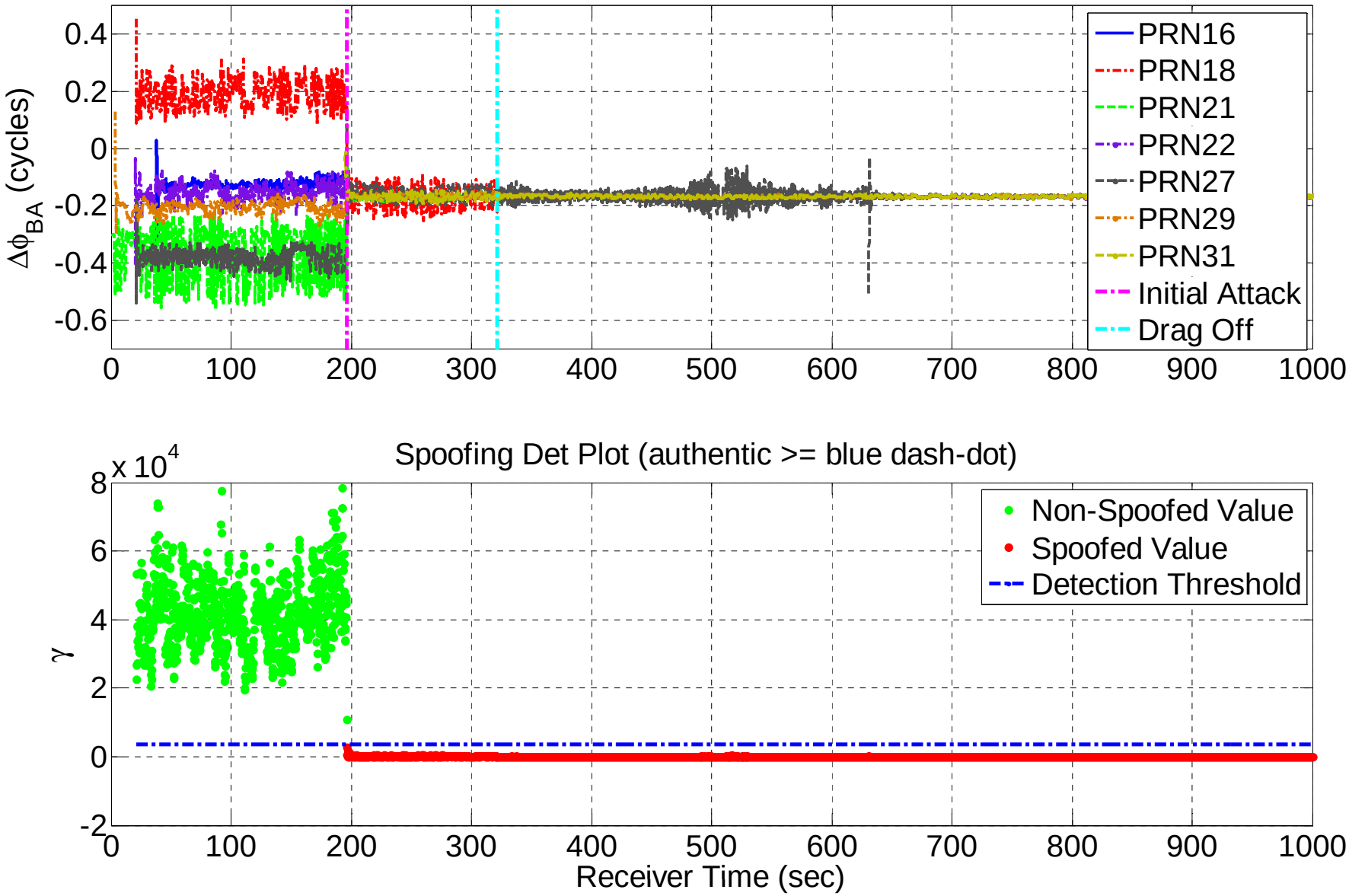
Movies: Initiation of Libya Spoofing Attack & Detection

- Download a 305MByte .zip-file of videos (http://gps.mae.cornell.edu/libyaspoofingattack_reenactmentvideos.zip)
- Unzip in order to view two short movies
- prelibyaspoof_markleadsdiscuss_00011.mp4
  - Brief explanation of what was tested during Libya spoofing attack
- libyaspoofattack_closeupoflaptop_markbrady extendeddiscuss_00013_00015.mp4
  - Techie's eye view of how spoofing detection system picked up Libya attack at its outset. Gives a "taste" of being there during the experiments

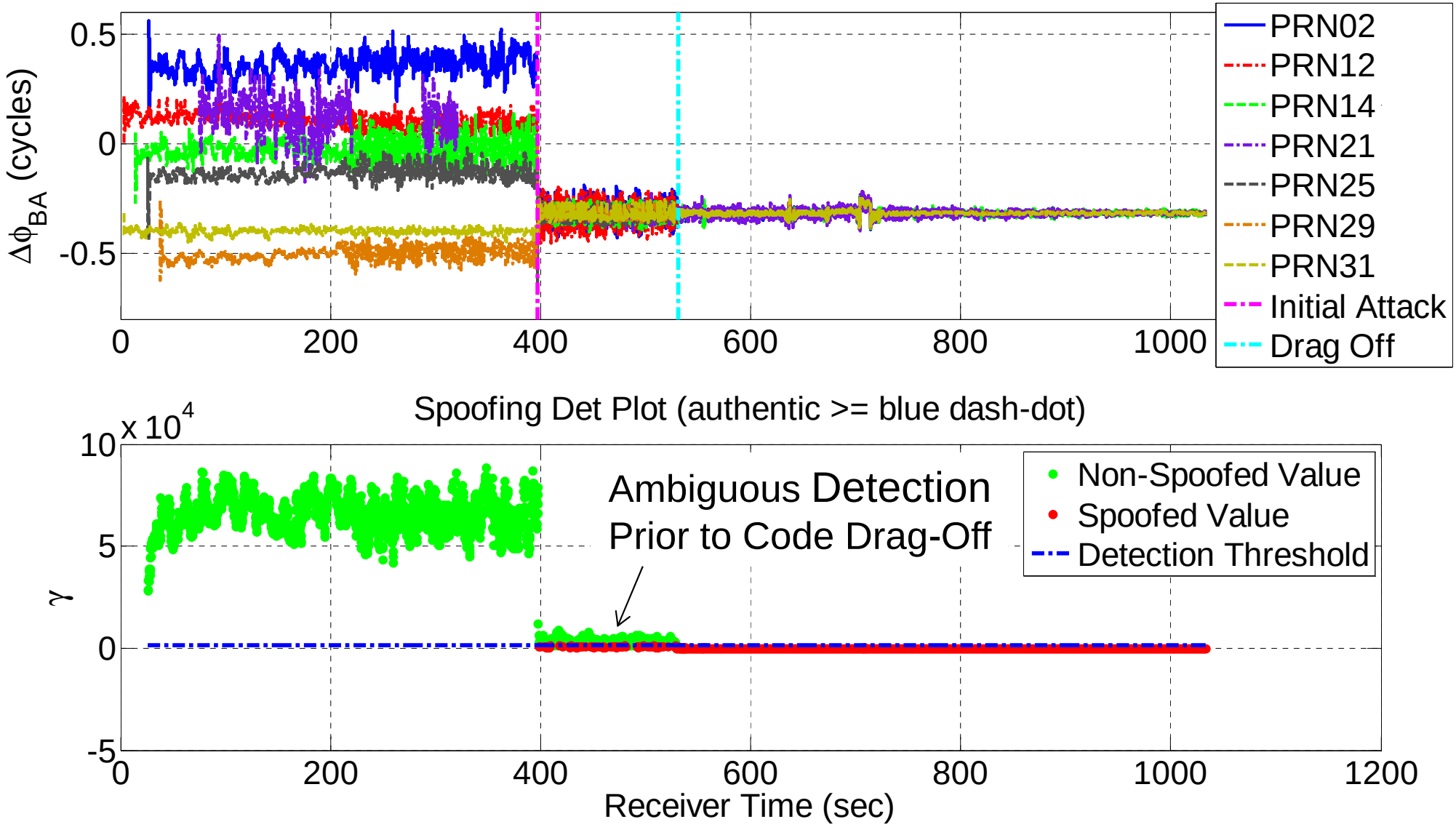
Highlights of Spoofed Trip to Libya



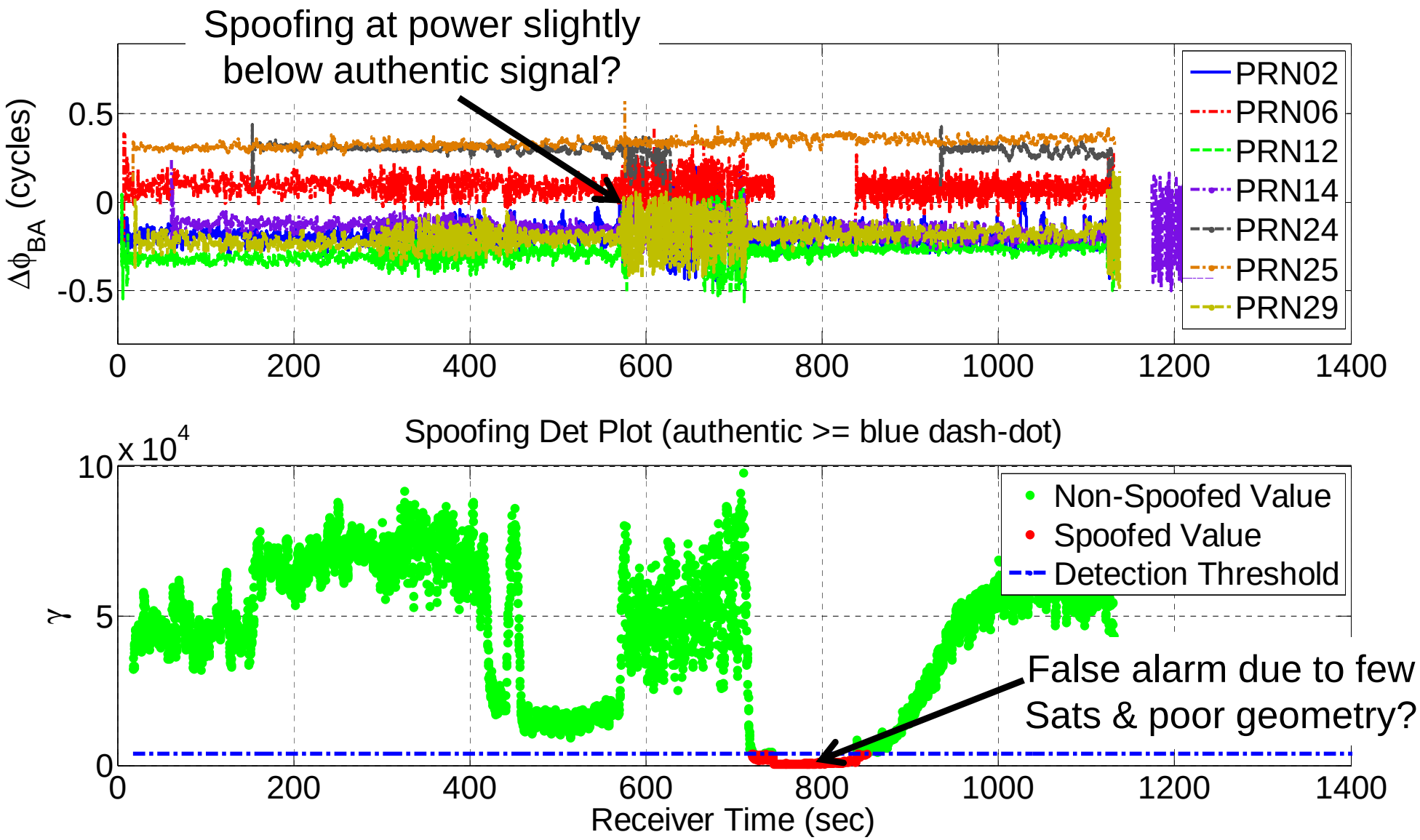
Detection of Attack During Libya Trip



Detection of More Subtle Attack

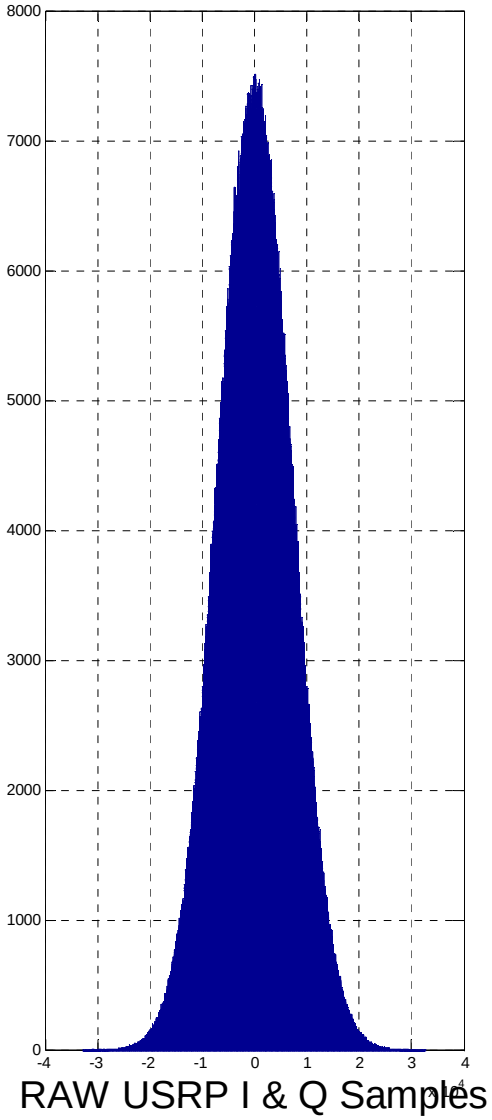


Failed Detection of Failed Attack

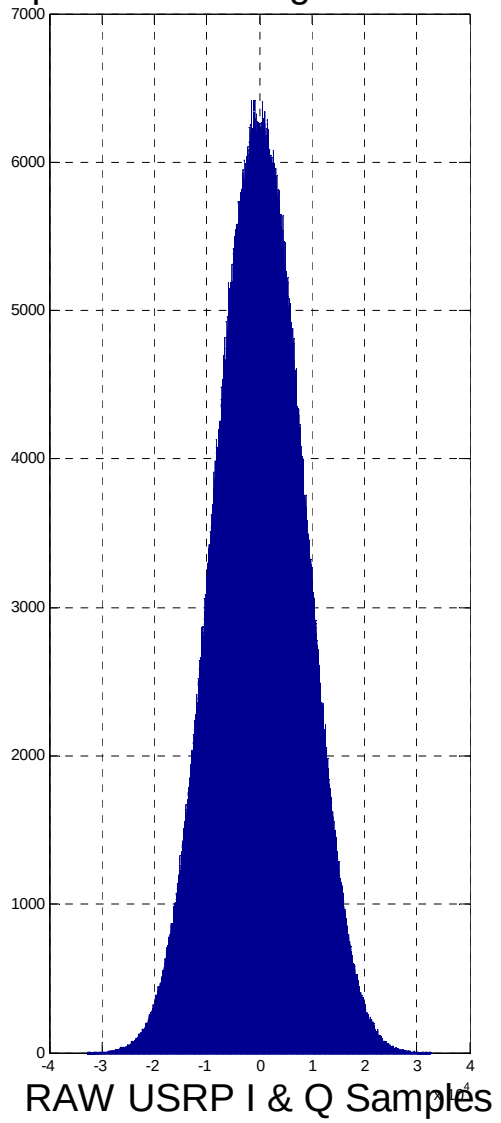


Comparative Histograms of RF Samples

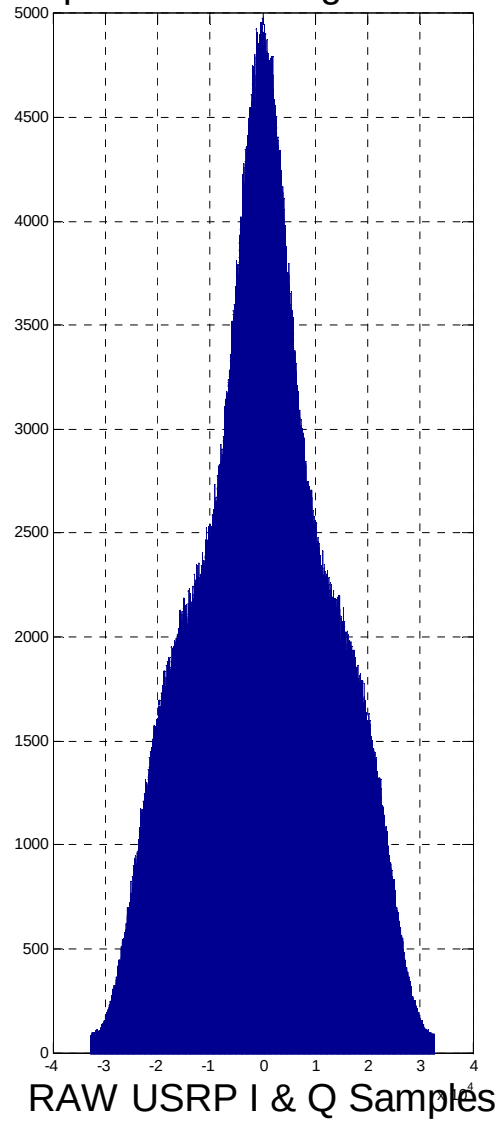
Authentic: σ = 7100



Failed Attack σ = 8200
Spoofer Advantage <= 0.9 dB



Successful Attack σ = 12500
Spoofer Advantage ~ 7 dB



Lessons Learned, Expected & Unexpected

- Initial capture & pre-drag-off is a challenge
  - Incomplete transition of differential phases (expected)
  - Difficulty of tracking thru alternating constructive & destructive interference between true & spoofed signals if spoofer power advantage not large (unexpected)
- Successful attacks not easy
  - Inexperienced spoofer operator needed to overwhelm true signals in victim receivers
  - Simple absolute power tests could have detected spoofing in these “sledgehammer” spoofing cases

Summary & Conclusions

- Developed real-time prototype of two-antenna spoofing detection
  - Exploits differing reception geometry between non-spoofed & spoofed cases: spoofing removes the natural differences between single-differenced carrier phases
  - Optimization-based data fitting leads to powerful detection tests
- Demonstrated real-time detection of live-signal spoofing attacks
  - Detections possible in 0.2 sec, depending on PLL bandwidth.
  - Tests less certain during initial capture period before code drag-off if spoofer power not much greater than authentic signal.

Future Plans

- Improve receiver tracking robustness during initial attack
- Implement real-time switched antenna version w/new PLL
- Develop additional spoofing tests for layered defense
  - Simple in-band power monitor
  - Advanced RAIM at discriminator/tracking-loop level
  - Compass continuity for 2-antenna system estimated attitude
- Improve & test methods for case of spoofing subset of signals
- Develop methods to recover true signals
  - True signals have been acquired during times of strong spoofing attack in recorded White Rose wideband data sets
- Test improvements with recorded White Rose data
- Test improvements in new live-signal tests against a subtle spoofer (requires another cruise!)