ICAO GNSS RFI Mitigation Plan
and associated EUROCONTROL Efforts

Gerhard BERZ
Focal Point Navigation Infrastructure
ATM Directorate, Research & SESAR Division, NAV & CNS Unit

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EUROCONTROL

Overview

This work has been supported by SESAR, Eurocontrol Network Manager and the GSA

- High Level ICAO Provisions
- GNSS RFI Mitigation Plan Overview
  - Principles
  - Regional and Global Support to States
- Summary of Supporting Developments Plans
  - Short, Medium & Long Term Detection Capabilities
    - “Closed Loop GNSS Service Provision”
  - Intervention Capabilities to Locate and Stop RFI Events

State Responsibilities: ICAO ANC/12

Recommendation 6/8 – Planning for mitigation of global navigation satellite system vulnerabilities

That States:

a) **assess the likelihood and effects of global navigation satellite system vulnerabilities in their airspace and apply, as necessary, recognized and available mitigation methods**;

b) *provide effective spectrum management and protection of global navigation satellite system (GNSS) frequencies to reduce the likelihood of unintentional interference or degradation of GNSS performance*;

c) *report to ICAO cases of harmful interference to global navigation satellite system that may have an impact on international civil aviation operations;*

d) *develop and enforce a strong regulatory framework governing the use of global navigation satellite system repeaters, pseudolites, spoofers and jammers*;

e) allow for realization of the full advantages of on-board mitigation techniques, particularly inertial navigation systems; and

f) where it is determined that terrestrial aids are needed as part of a mitigation strategy, give priority to retention of distance measuring equipment (DME) in support of inertial navigation system (INS)/DME or DME/DME area navigation, and of instrument landing system at selected runways.

ANSP Responsibilities: ICAO GNSS Manual (Doc 9849)

- 5.1.5 State regulators and **ANS providers can take the measures described in this chapter** to reduce the likelihood that GNSS service will be lost.
- 7.11.3.1 **ANS providers must be prepared to act when anomaly reports** from aircraft or ground-based units suggest signal interference. If an analysis concludes that interference is present, ANS providers must identify the area affected and issue an appropriate NOTAM.
- 7.12.5 **National and international coordination of actions to prevent and mitigate GNSS interference is essential**.
- 7.13.1.1 As described in Chapter 5, States can **take measures to reduce the likelihood of service outages** due to unintentional and intentional signal interference. **ANS providers must still, however, complete a risk assessment** by determining the residual likelihood of service outages and the impact of an outage on aircraft operations in specific airspace.
- Appendix B, Roles of ANS Providers and Regulators: **ANSP to establish appropriate strategies to mitigate GNSS outages**, Regulator to validate the safety aspects of the mitigation strategies.

Introduction to RFI Mitigation Plan

- GNSS RFI Mitigation Plan History & Context
  - Initiated by Spring 2013 Workshop at Eurocontrol Navigation Steering Group Meeting
    - State / ANSP contributions on best practices
  - Guidance developed through ICAO Navigation Systems Panel
    - In response to ICAO 12th Air Navigation Conference Job Card
  - Inclusion in GNSS Manual, ICAO DOC 9849
    - Completed Navigation Systems Panel review, final review and adoption planned for NSP/3 in DEC 2016
    - Strongly supported by Airlines (ICAO Assembly Paper)

- Scope
  - Limited to threats requiring radio frequency propagation
  - Not dealing with corruption of position once it has left receiver

Moving from Vulnerability to Mitigation

- Objective of RFI Mitigation Plan
  - **Define set of activities for States to ensure that risks to aviation from GNSS RFI are sufficiently mitigated**
  - Checklists of set of activities to be considered
  - Much is already in place, State to decide depending on local environment
  - *Not intended to impose a significant workload or investment*
  - To enable reliance on GNSS and associated aviation benefits

- Focused on States
  - Spectrum a sovereign responsibility
  - Regulation and enforcement part of national oversight
  - Framework to encourage coordination and exchange of best practices
  - Supported by regional and global mechanisms due to system nature

Mitigation Plan Framework

Monitor Threats

1

- Proactive & Reactive Monitoring
- Environment Evolution

Assess Risks

2

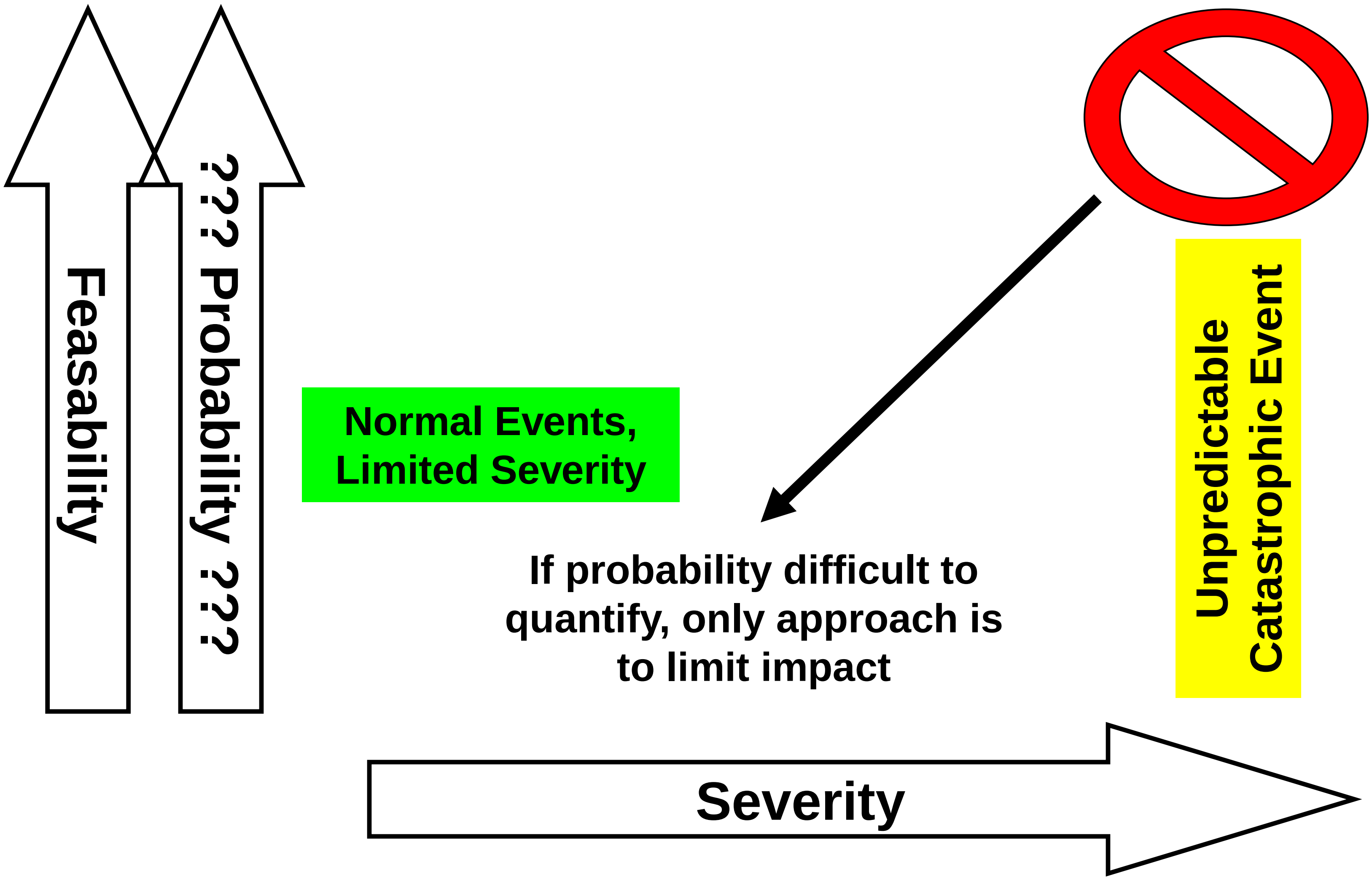
- Scenario Variation & Escalation
- Impact Assessment
- Identify Existing Barriers

Deploy Mitigation Measures

3

- Reduce Risks to Acceptable Levels
- Integrate in SMS

Risk Trade Space



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Implementing Mitigation Barriers

Prevent Transmission of RFI

- Regulatory Control and Enforcement
- Outreach

Prevent GNSS Service Outage

- GNSS Resilience
- On-board Integration

Limit Severity of Impact

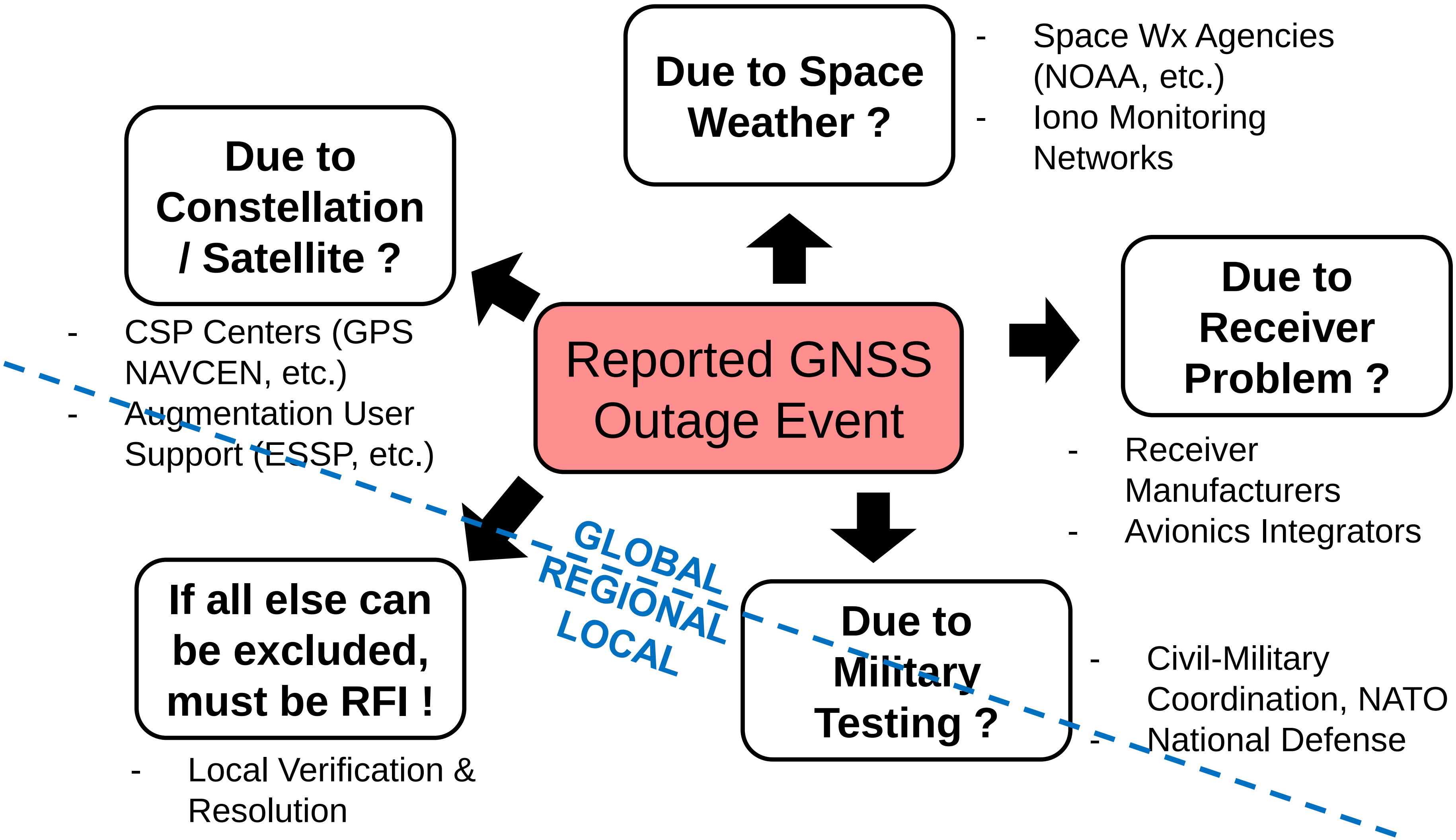
- CNS/ATM Integration
- A-PNT
- **Detection & Resolution**

GNSS RFI Vulnerability

Supported by Threat Monitoring Networks
(Preventive & Reactive Role)

Note: Limiting "success probability" of intentional RFI limits likelihood of events (exposure to detection)

Identification of Probable Cause Through Elimination



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GPS OUT Reporting Streams Today

GNSS Multi-Modal
Aviation one User among many

Aviation Specific
GNSS Out One Issue among many

GPS NAVCEN

IATA

AO

- Airline OPS Center
- FOQA Monitoring?
- PIREP: Local AIS

ESSP

Eurocontrol Network Manager

Local ANSP ?

- AIS to Technical Services
- Technical Services activate subsequent process?

No aggregate vision of events → Incomplete threat picture
Resolution depends on awareness of many individuals

Meeting "Stated ATCO Requirement"

- Budapest GPS Outage Simulations:
  - **"Tell me when event starts, when it ends, and how many sectors are affected"**
  - No simple technical solutions exist today
  - Allows contingency planning through planner ATCO

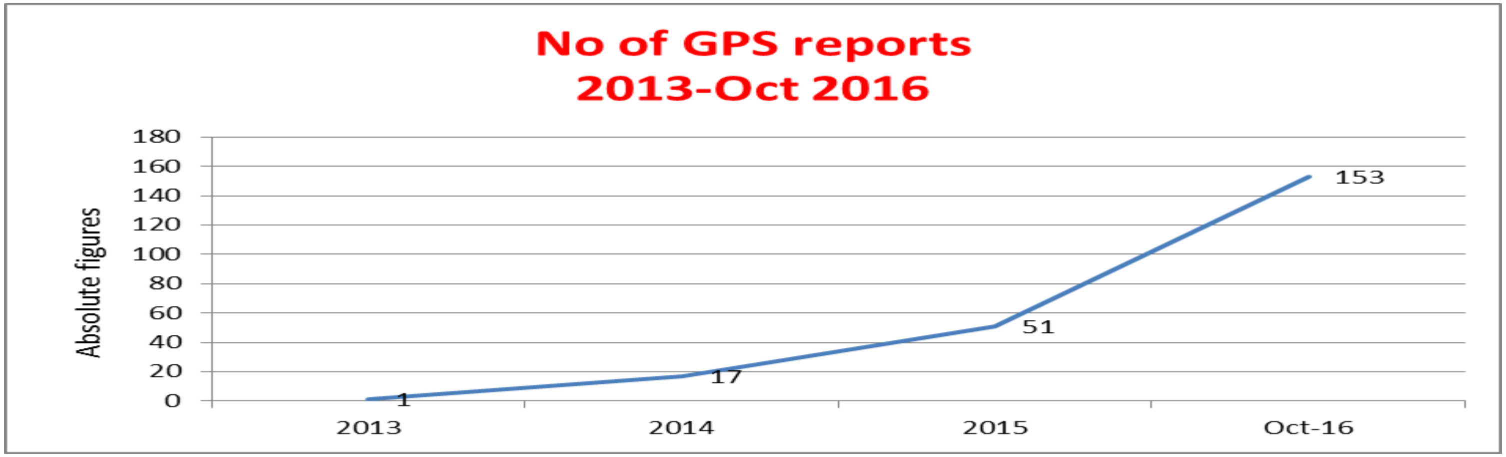
- **Best to monitor at the impact source: aircraft receiver**
  - Currently, only pilot can observe receiver outage
  - Subsequent reporting requires support at regional and global level to determine probable cause (only RFI is local problem)
  - Provides essential risk assessment link on operational impact

ATCO = Air Traffic Control Officer

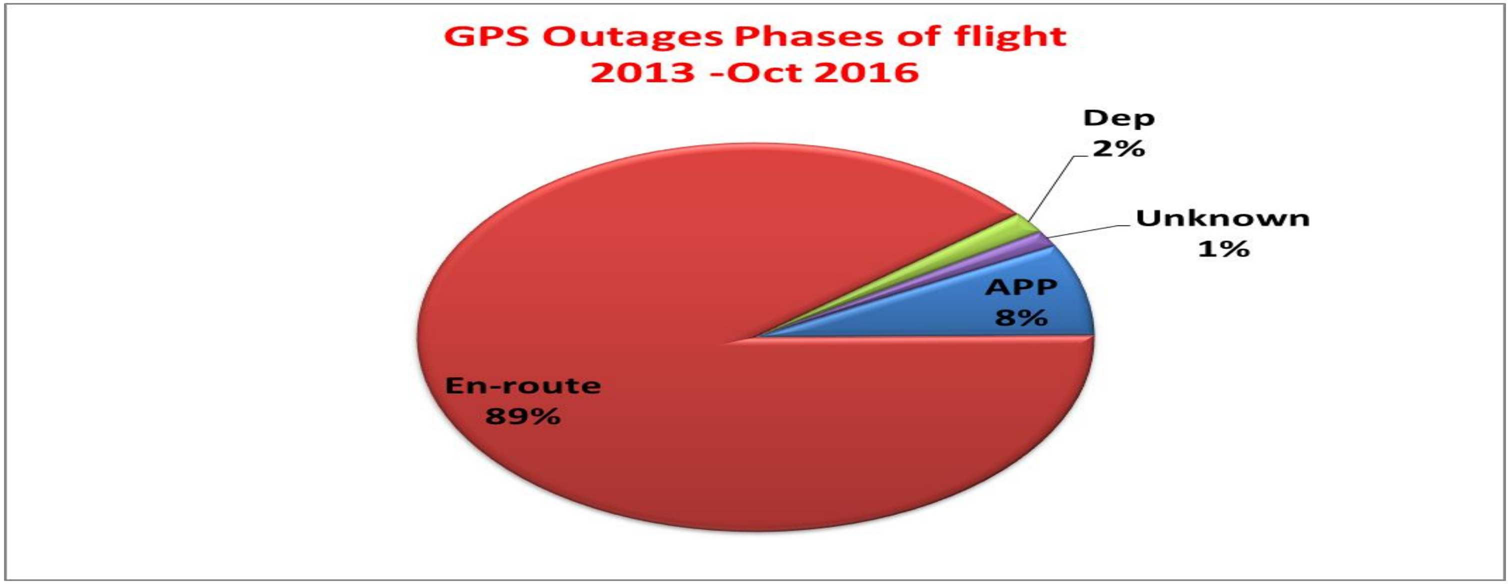
Implemented: GNSS in EVAIR

- EVAIR = Eurocontrol Voluntary ATM Incident Reporting
  - Established Safety Process (Confidentiality, Anonymity)
  - 250 Participating Aircraft Operators
  - Coverage: Europe, Middle East, Northern Africa
  - Close cooperation with IATA
  - Part of Network Manager Functions
- Info Bulletin sent beginning 2015 and mid-2016
  - Initial wave of reports received covering 2013/2014
  - Additional reports coming in every few weeks
  - GNSS Outage one issue among many
  - Simple to set up because it is an existing process / framework
  - Working on further awareness materials

GPS Outage Reports in EVAIR

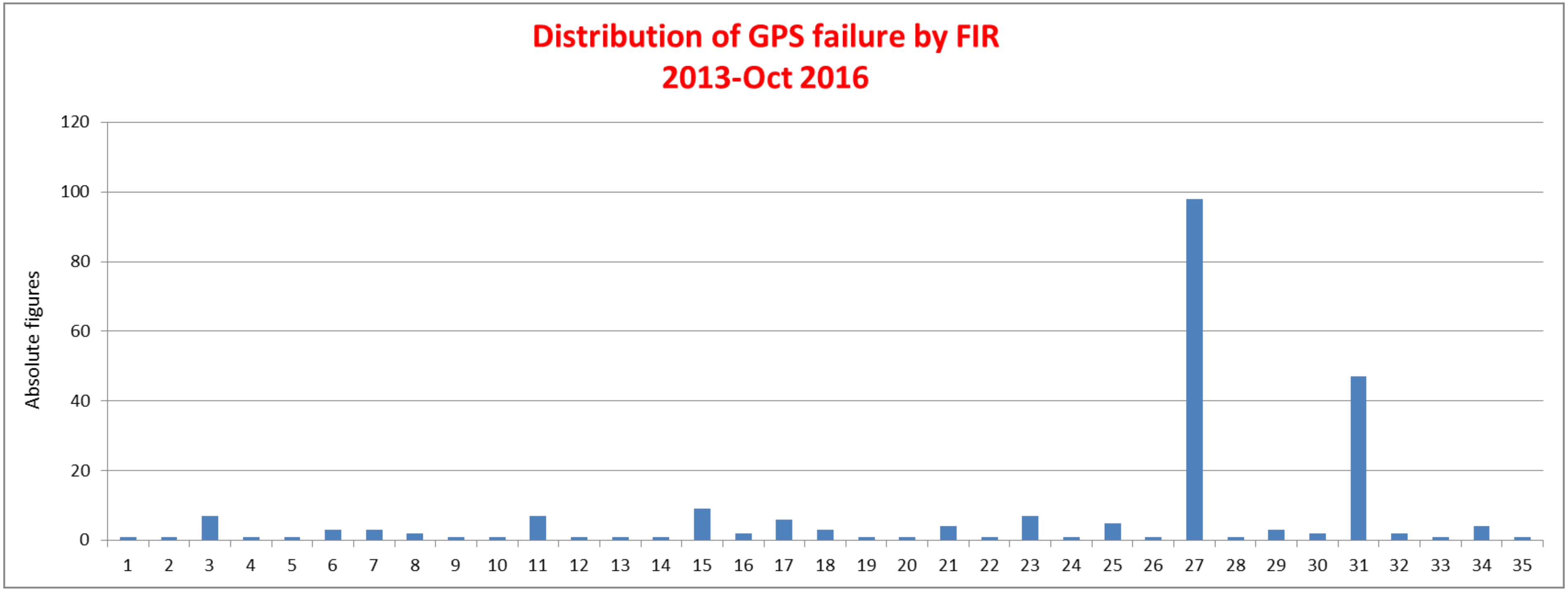


Steady increase especially in 2016



En-Route is most affected flight phase!

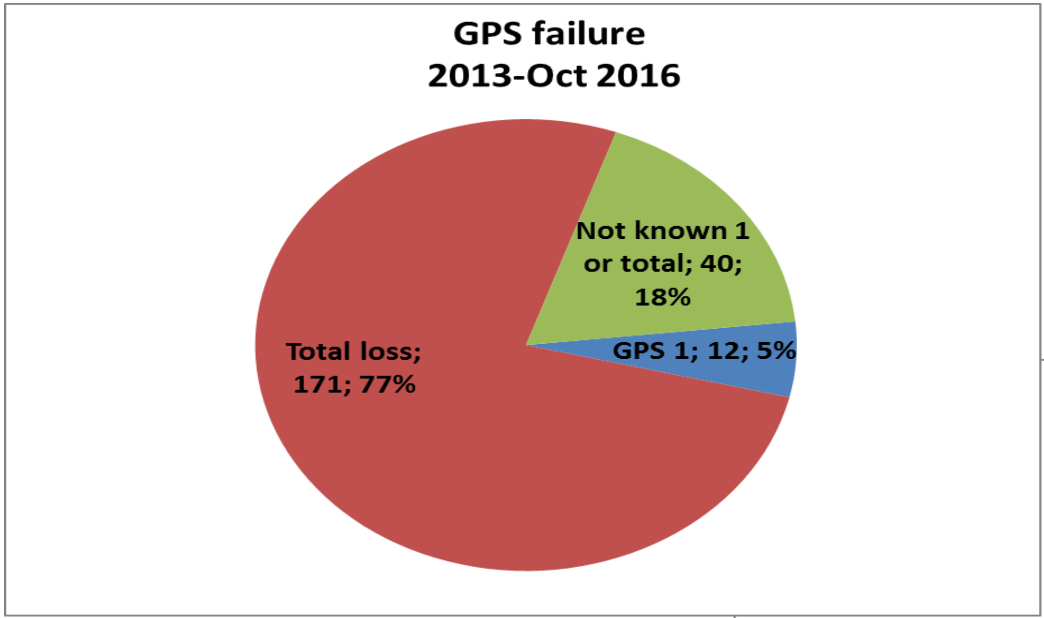
Note: GPS OUT Report does NOT necessarily equate to RFI Event!



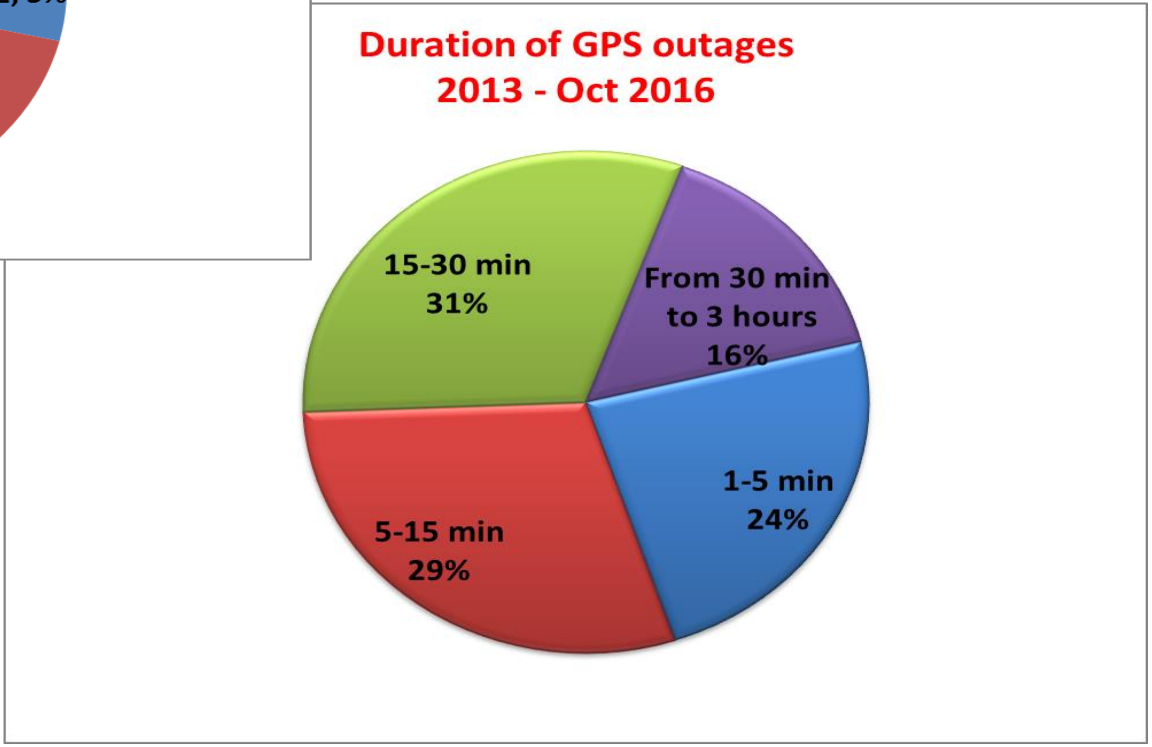
FIR = Flight Information Region

Other recent significant (confirmed) RFI cases: Sydney, Korea, Cairo, Madrid, Ankara, several (smaller cases) in France

GPS Outage Type and Duration

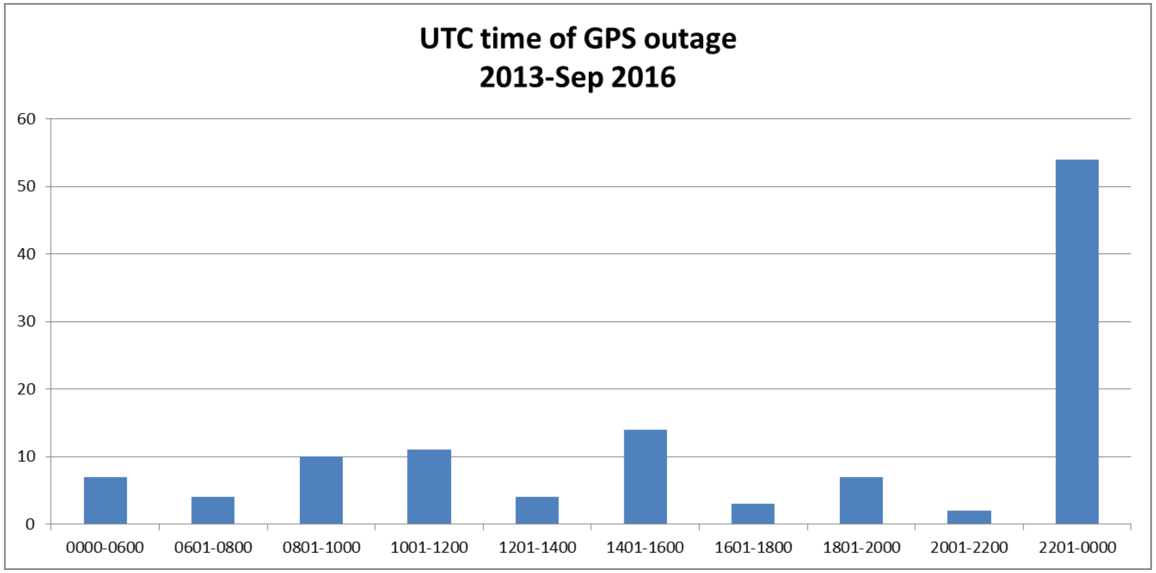


GPS Function normally regained during flight

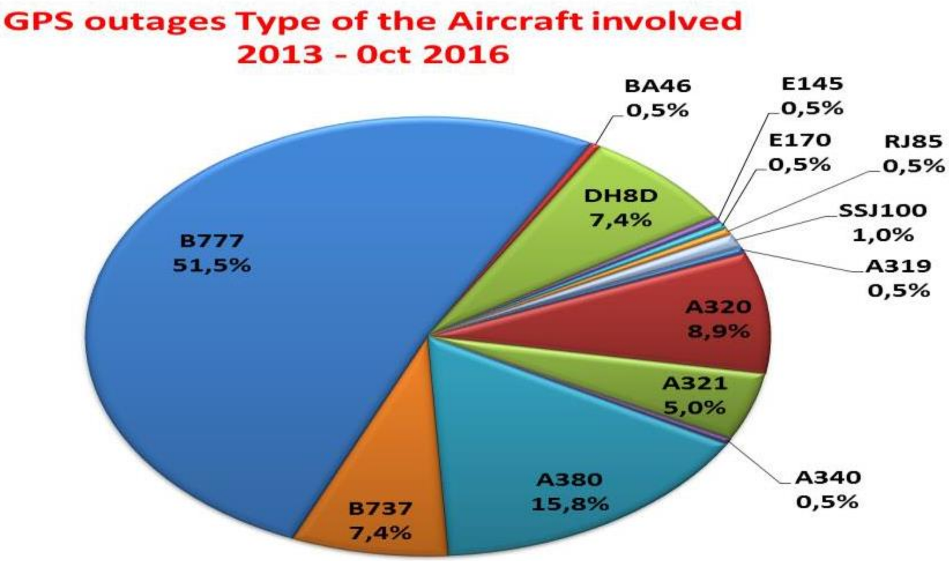


Pilot reporting details and avionics impact vary

GPS Outage: Time and Type

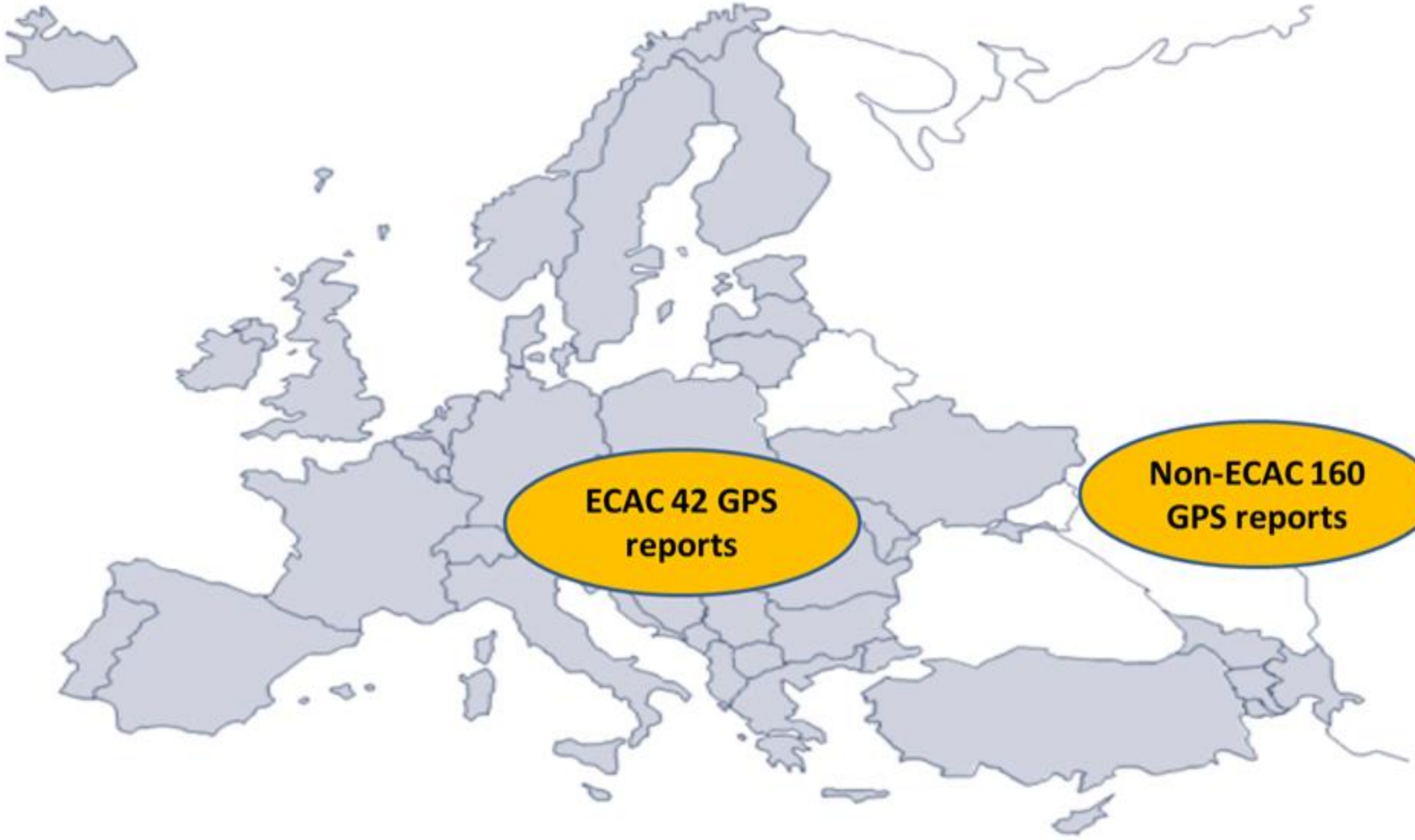


Most Events Occur at Night!



B777 is most flown type in areas most affected

Geographic Distribution of Events



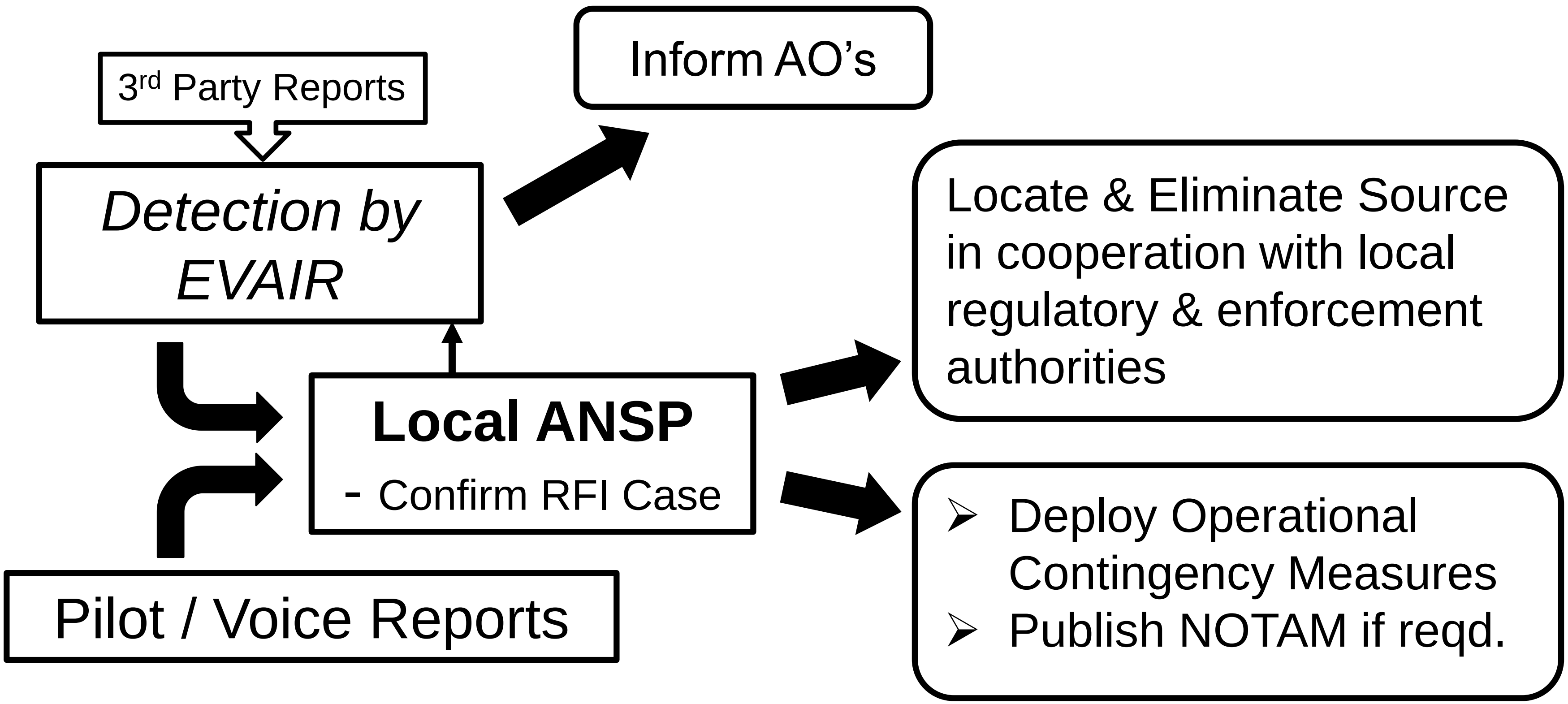
ECAC = European Civil Aviation Conference

GNSS in EVAIR: Threat Monitoring

- Return to normal operations & impact on both receivers on few aircraft point to RFI with high probability
  - **Proves that RFI Outages are REAL but also limited in operational impact currently**
- Time-limited, single events do not warrant action
  - **Supports strategic objective of threat monitoring**
  - Enables setting boundaries on event probability and severity
  - Provides detection if environment changes
- Maintain central repository and statistics of GNSS Outage events
  - Consultation of GNSS service and space weather monitoring reports provide further refinement
  - May also benefit from data from local ground receivers
  - Clarify interfaces for aviation-relevant reporting

EVAIR: Trigger for Detection & Mitigation

- Significant accumulation of events in specific area leads to detection and triggers mitigation action
- Ensuring timely resolution reduces vulnerability / exposure



Interfaces with GNSS System Operators (GSO)

- Currently, mainly GPS NAVCEN and ESSP
  - Multi-constellation: GLONASS, Galileo, Beidou Service Centers
  - Regional SBAS User Support Centers (GBAS with local ANSP)

- **Case 1: Strategic Long Term Threat Monitoring**
  - Info from GSO to Aviation: Ensure comprehensive view of all aviation-relevant cases

- **Case 2: Tactical Mitigation: Actual Significant Outage Event**
  - Request from Aviation to GSO: Support in identifying probable cause
  - Benefit from established links (receiver issues, ionosphere, RFI testing)

Further Efforts & Ongoing Developments

- Medium Term
  - Use of ADS-B Position Integrity Category (PIC) Reports
    - Initial studies conducted, various issues
    - Derive independently on ATC side large area RFI event
  - Use of aerial work aircraft to quickly locate RFI sources
    - In cooperation with ground based resources
    - Studied use of Controlled Radiation Pattern Antenna
    - Significant increase in esp. broadband RFI localization sensitivity
- Long Term
  - Nest generation GNSS receivers: detect RFI and provide information to ATC

Summary

ICAO GNSS RFI Mitigation Plan

- Mature and available to States
- Hope to learn from feedback from local implementation

Regional and Global Support Process being put in place

- EVAIR Data and Network Manager Process
- Continuing work on appropriate airborne monitoring capabilities
- Continuing work on increased intervention capabilities
- ATCO training can mitigate until next generation capabilities in place

A lot can be done with relatively simple means

- So far, GNSS RFI threats have not lead to significant risks to aviation operations
- Continued cooperation and development of RFI vulnerability mitigation capabilities can ensure that this remains the case
- To enable full exploitation of Operational GNSS Benefits

Requests to UN ICG

- Support information exchange for aviation with GNSS system operators
  - For both threat monitoring and significant event mitigation
  - Help to identify non-RFI causes
- Forward aviation relevant reports to relevant entities (States, Regional Organizations)
- REF Slide 10 and 21

Back-Up

- Mitigation Plan Details
- Further EVAIR Details
- ADS-B based Monitoring
- CRPA Project Results

Operational Risk Context

- “Loss of Nav” is an event that each aircrew needs to be prepared for at any time
  - Safety Procedures are in place
- Potential of Wide Area GNSS Outage: ATM Context
  - Especially in busy airspace, significant workload risk if many aircraft ask controller for navigation assistance
  - Very busy airspaces tend to be mainly vectored already but move to PBN should reduce this
  - NAV has multiple roles including pilot SA to manage flight
- Reversion Scenarios for PBN
  - Majority of Air Transport Users has DME/DME and INS
  - “Budapest Real Time Simulation”
  - VOR/DME does not provide suitable RNAV capability
  - PBN implementation planning
  - ICAO Annex 10 NAVAIDS Strategy

Threat Types

- Unintentional
  - TV Broadcast Harmonics, Equipment Failure
- Intentional, not directed at aviation
  - Avoiding charges or tracking
- Intentional, directed at aviation
  - Ranges from nuisance to military threat
- Special Types
  - Military Testing
  - Spoofing

- Classification drives mitigation strategies

Key Starting Challenges

- **Observability** of RFI Events
  - Lack of reports does not mean that RFI cases don’t exist
  - Existing Spectrum Groups receive few reports
  - NOTAM search produced few results
    - Standardized terminology developped
  - Need to know what happens at aircraft!

- **Confirmation** of RFI Event
  - Difficult to conclude that GNSS outage is result of RFI
  - All other causes of outages are not local ANSP issue

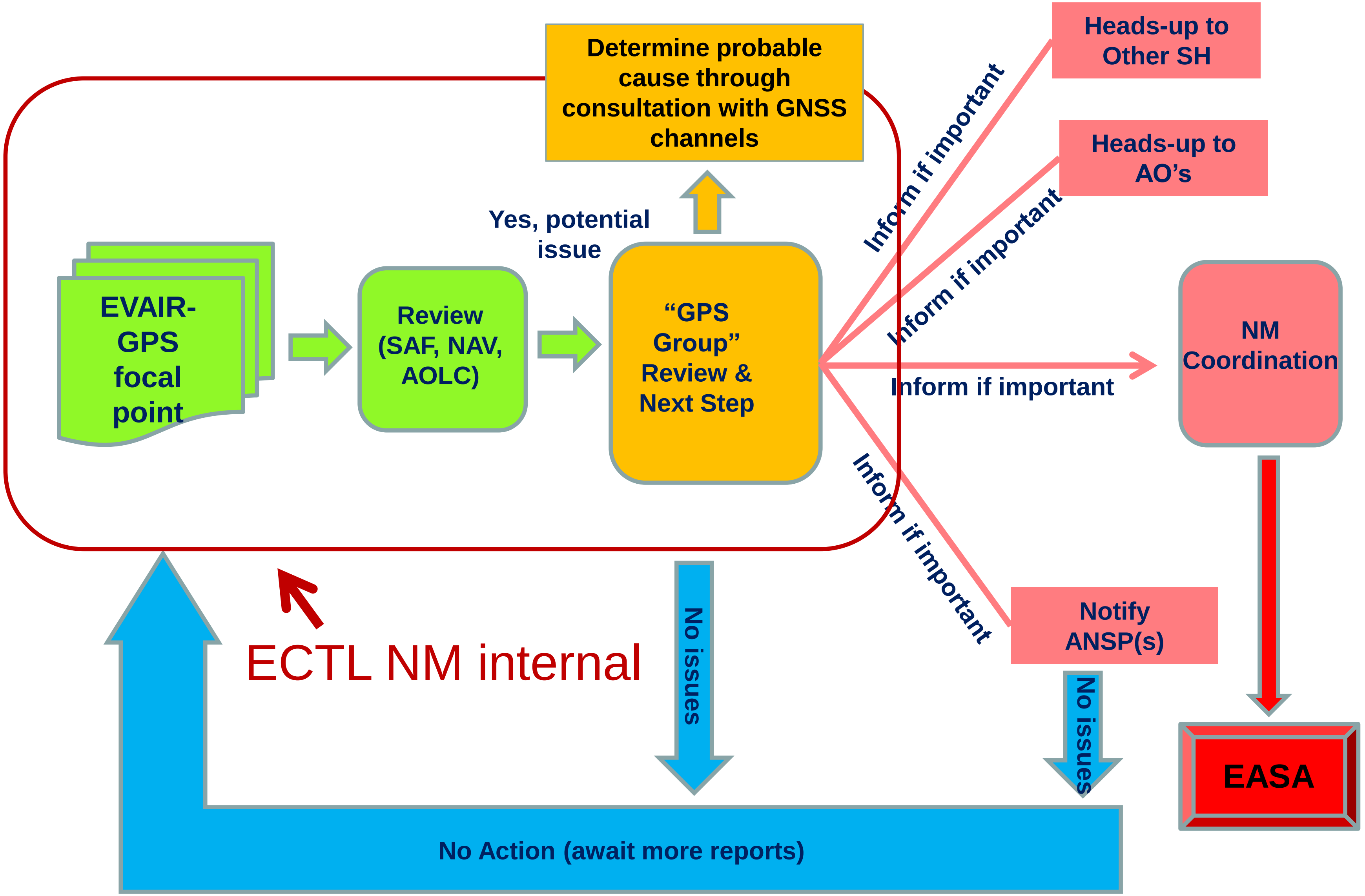
- Both Challenges require State-external support

Generic RFI Mitigation: 4 Steps

*Note: applies to **all** RFI types & scenarios!*

1. **Detection** of RFI
   - Ground monitoring networks (aviation & non-aviation)
   - Pilot reports: difficulty in cause-effect recognition & subsequent processing
     - Automated in-flight detection would be better?
   - Flight Inspection: continuous or on occasion (non-uniform capabilities!)
   - Determination of affected area and impact critical to launch response
2. **Localization** of Source: ranges from simple to extremely difficult
   - In cooperation with telecom regulator / affected non-aviation parties
   - Identification of operator
3. **Termination** of RFI:
   - Need clear legal basis and resources for enforcement action
   - Cross border issues can be lengthy to resolve
4. Application of **Consequences**: fine, publicity - future deterrent
   - Update of RFI Mitigation planning as needed

EVAIR GPS *Mitigation* Information Flow

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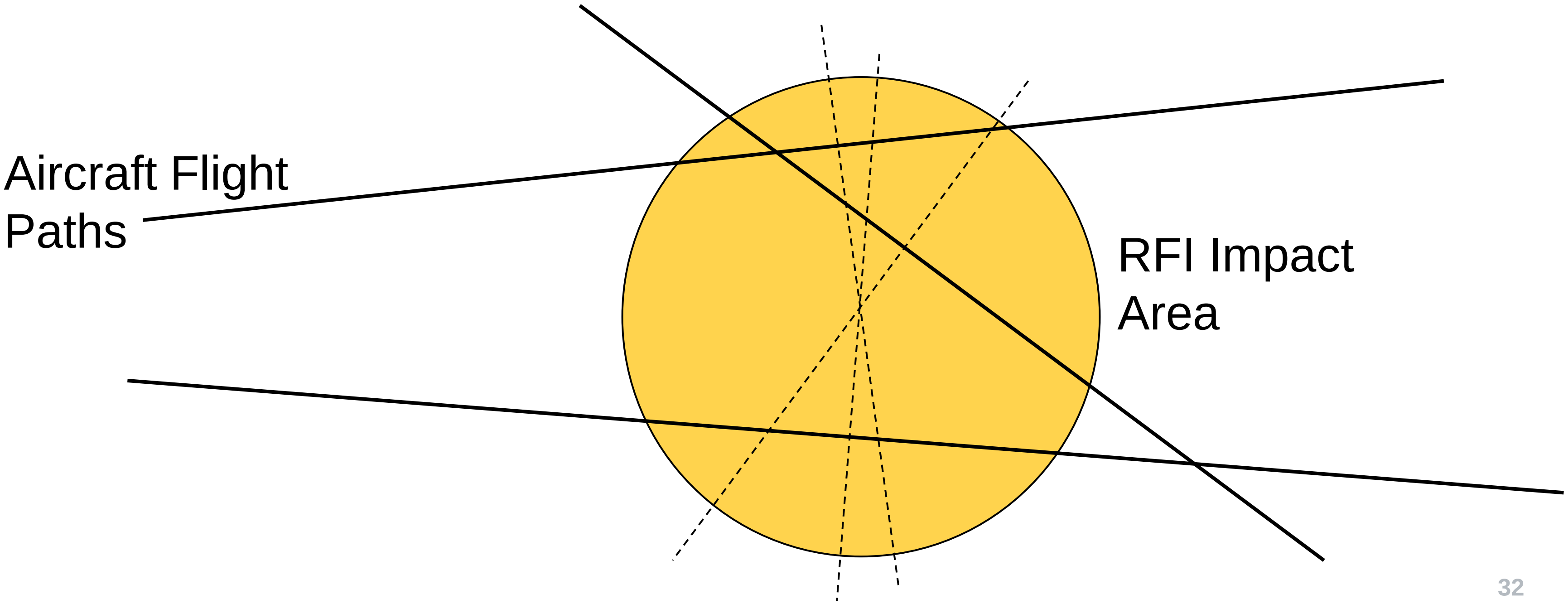
EVAIR Report Possibilities?

- If precise report of start and stop coordinate of outage event are known, bisector line of potential RFI source location can be derived
  - Assumes omnidirectional RFI source
  - Multiple aircraft reports could lead to localization
  - Requires data support from airline
- Within limits, a minimum power level can also be hypothesized



Medium Term Improvements (1 of 2)

- Not really Pilot's job to determine cause of GPS outage or to report signal in space issues
  - In the age of SWIM, should be automated
  - RFI detection standard feature in many commercial receivers

- CNS Idea: Reporting through ADS-B Figure of Merit
  - Part of ongoing investigations
  - Feasibility demonstration: Australia
  - Demonstrated benefit of air-ground cooperative approach
  - Need to test and build experience in how to integrate information
- Some guessing remains with respect to probable cause
  - Especially for wide-area outage where resolution should be fast
  - Serendipitous capability, but not ideal

ADS-B PIC Use for GNSS Monitoring

- ADS-B:
  - Different versions of the ADS-B Out MOPS in use
    - Different ways to encode integrity
  - Not all aircraft are “proper” ADS-B Out:
    - Version 0 implemented on voluntary basis (along with Mode S mandates, ADS-B only certified on a non-interference basis)
    - Later AMC 20-24 certification only applies to subset of fleet
    - Not necessarily using GNSS as position source
    - Some known avionics issues with version 0

- GNSS:
  - Different levels of performance
    - Limited information about the position source (SA On/Off, SBAS etc.)

ADS-B based GNSS Monitoring: Issues

- Difficult Capability to Test without significant RFI Event
  - Study tried to correlate ADS-B Position Integrity Category with events:
  - Known RFI Events
  - Predicted RAIM Outages
  - Iono Events
  - None of the investigated events produced reliable correlation

- But learned about use of ADS-B data
  - Careful filtering of reliable data – establish white list?
  - On-board issues usually result in a certain NUCp/NIC behaviour
    - not so common – can be filtered out
  - Most of the fleet has stable quality indicators
  - SPI IR implementation of ADS-B Out version 2 (ED-102A / DO-260B) expected to further improve the picture

- **Still think that method has promise at least for “massive” RFI events**

Sydney Case: ADS-B Lessons Learned

- ADS-B reports key to identifying probable source location: Aerospace Industrial Park
  - "Search" proved sufficient to terminate 3h event
- Most Ground Monitor Stations didn't see RFI
  - Some outages on WAM network, but difficult to locate
  - Need to evaluate line of sight

- Lessons Learned
  - Aircraft with INS didn't lose NAV
  - Contingency procedures worked
  - Some aircraft GPS receivers didn't recover (even on turnaround!)
  - Air Services Australia recommends recording of GPS status on QAR
  - Ground and aircraft based localization must work in complement
  - Implementation simplest if within existing processes & infrastructure

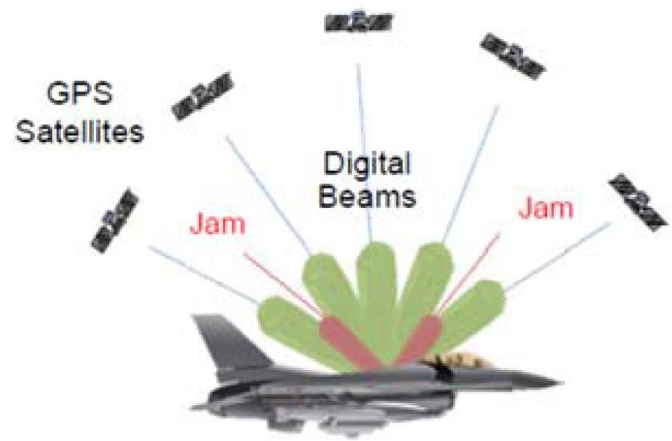
Position Integrity Category

- Ground system notation (Asterix) for integrity containment bound encoding

PIC	Integrity Containment Bound	NUCp ED102/DO260	NIC (+ suppl.) DO260A	NIC (+ suppl.'s) ED102A/DO260B		
				NIC	A/B	A/C
15	not defined					
14	< 0.004 NM	9	11	11	-	-
13	< 0.013 NM	8	10	10	-	-
12	< 0.04 NM		9	9	-	-
11	< 0.1 NM	7	8	8	-	-
10	< 0.2 NM	6	7	7	-	-
9	< 0.3 NM	-	-	6	0/1	1/0
8	< 0.5 NM	5	6 (+ 0)	6	0/0	-
7	< 0.6 NM	-	6 (+ 1)	6	1/1	0/1
6	< 1.0 NM	4	5	5	-	-
5	< 2.0 NM	3	4	4	-	-
4	< 4.0 NM	-	3	3	-	-
3	< 8.0 NM	-	2	2	-	-
2	< 10.0 NM	2	-	-	-	-
1	< 20.0 NM	1	1	1	-	-
0	No integrity (or > 20.0 NM)	0	0	0	-	-

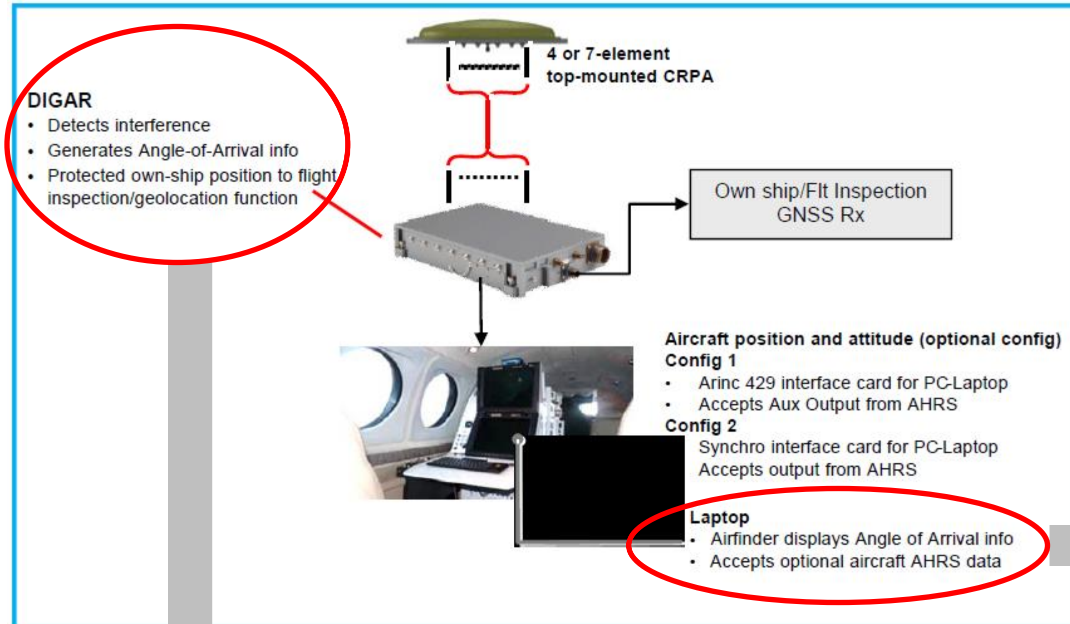
RFI Localization Developments

Medium Term Improvements (2 of 2)



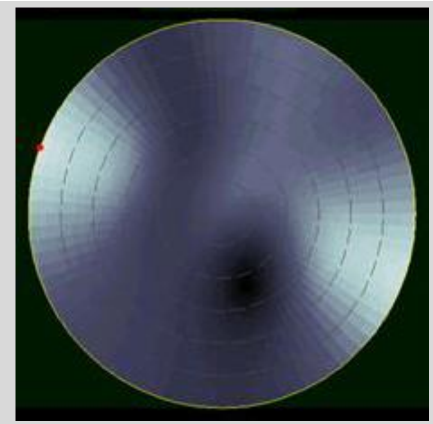
- Controlled Radiation Pattern Antennas CRPA
  - Multi-element GNSS antenna used in defence applications
  - Not an option for airliners, but maybe flight inspection aircraft?
  - Cooperative project with FAA and DSNA
- Project Goals
  - Develop and Demonstrate Concept & Feasibility
  - Increase localization antenna sensitivity
  - Maintain own-ship position during RFI
- Process
  - Directly obtain pointing to RFI source with reduced search time
  - Allow efficient deployment of ground capabilities
  - Reduce vulnerability by dramatically reducing intervention time

Can we use a “MOTS” Solution?



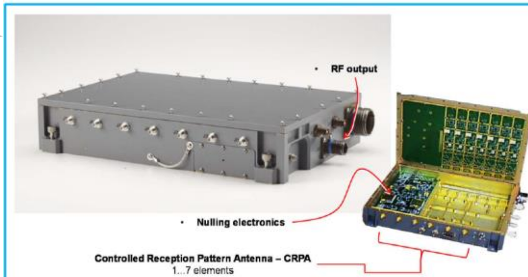
Proposed Principle of Operations

- Rockwell Collins DIGAR: Digital GNSS Anti-jam Receiver
- Algorithms able to detect wide range of RFI sources (Continuous Wave (CW), swept CW, Broadband, …)
- AHRS and Direct Geolocation Processing NOT YET implemented / investigated



- **White area: possible RFI direction**
- **Red dot: received power above specified threshold**

Jammer Direction Finder Display

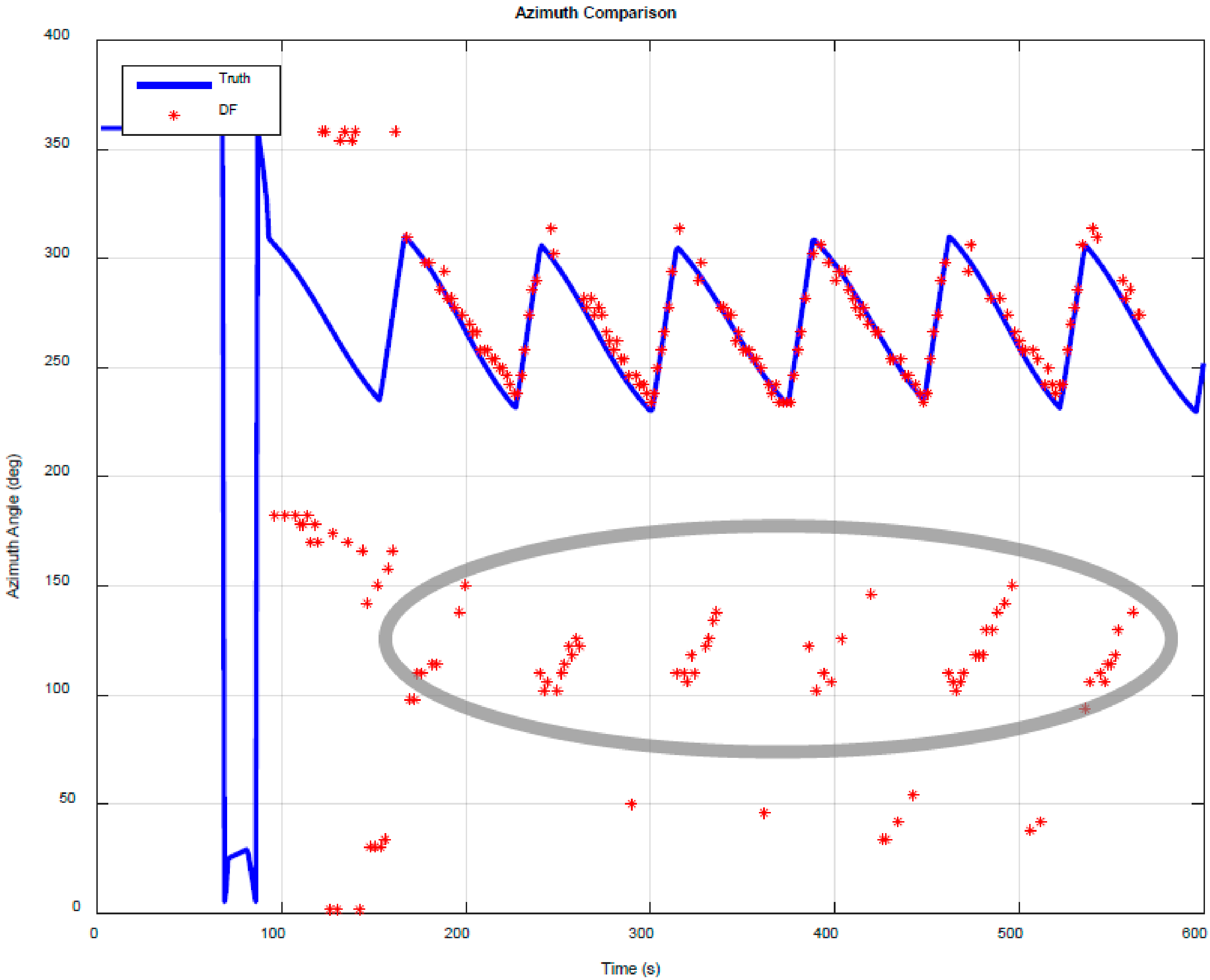


DIGAR

Installed system includes:

- CRPA
- Antenna & interface cabling
- DIGAR with GNSS Baseband Processing
- Laptop with DF Software

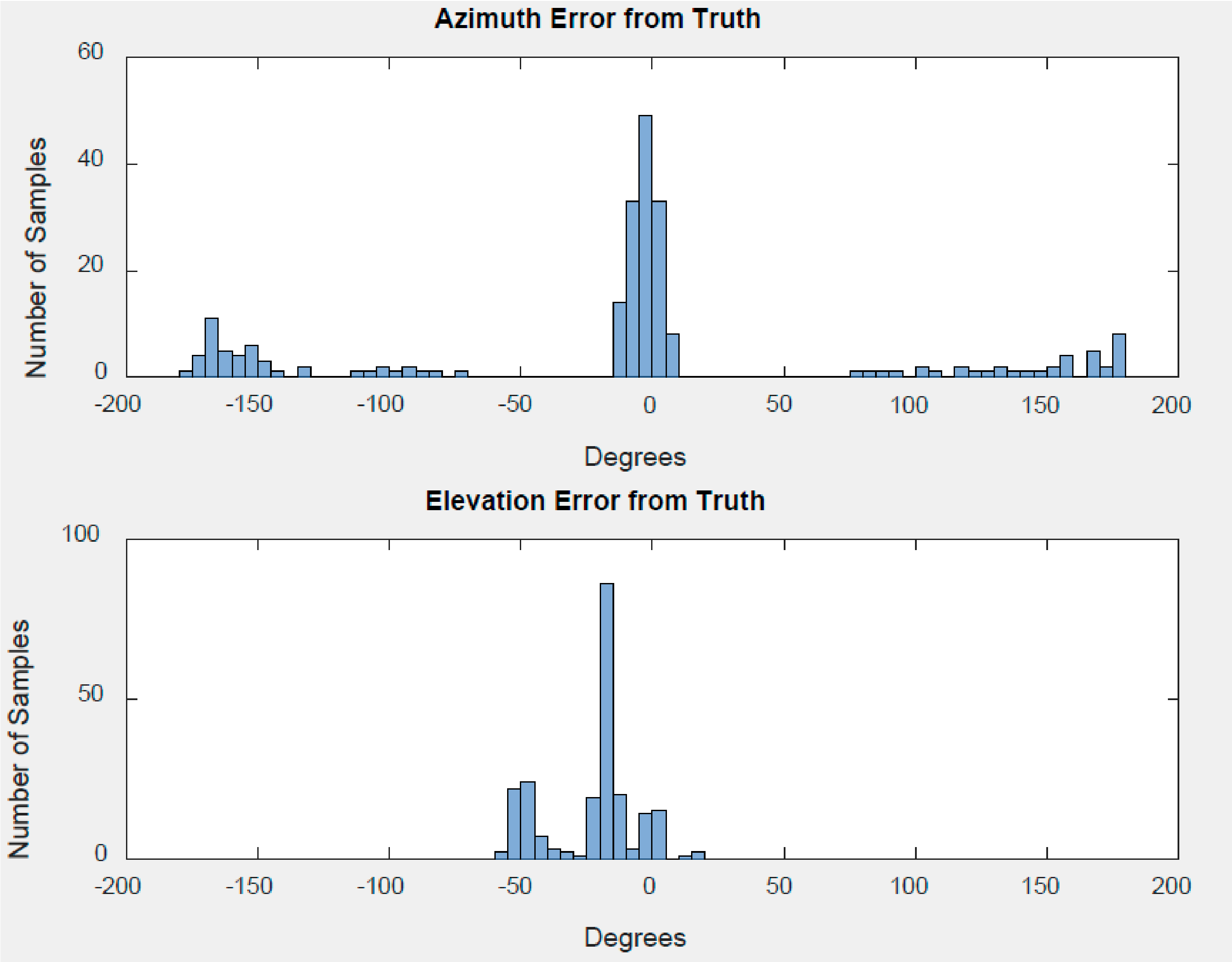
Lab Detection Performance (AZ)



- CW Azimuth Performance, Ground Support Loiter
- Good matches mixed with directional ambiguity

Sympathetic nulls typically move in the opposite direction

Lab Detection Performance Histogram



Test Results

- Trigger and Hunt search strategy not ideal
  - Figure 8 probably best
- Elevation information generally not useful with top mount CRPA
  - Consider extending DF processing to negative elevation angles
- Azimuth pointing better than ±10 degrees
  - Also when subject to ground multipath
  - Banking helps, but not dramatically
  - Detection performance not sensitive to signal type
- Need to develop smoothing filter to eliminate sympathetic nulls
  - Investigate algorithm with variable probability of false detection
- Overall results promising
  - Good match between wavefront simulator and van tests
  - AHRS and RF Calibration requirements acceptable for FI Orgs
  - Flight tests with fully integrated prototype would be useful

FAA Overflight: Technology Comparison

- Spectrum Analyzer and DF-4400 performance depend on correct mode selection and settings suitable to RFI source
- CW detection better with DF-4400, but worse for Broadband
- Bottom-mounted numbers estimated from lab measurements

[dBm]	DF-4400	CRPA System	CRPA System
Antenna Mounting	Bottom	Top	Bottom
Narrowband	-120	-115	-125
Broadband	-99	-115	-125

Conclusions of CRPA Project

- **FAA and DSNA both prefer bottom-mount option to improve detection performance**
  - Loss of ownship position not a significant concern when chasing weak RFI signal sources
  - FI A/C have alternate positioning capabilities
- **CRPA-based system has higher detection performance**
  - Especially for Broadband signals
    - Most PPD Signals are broadband
    - Estimated 25dB Improvement very significant
  - Not dependent on operator settings
  - Does come at an increased price
- **FI Organizations and Industry encouraged to further develop GNSS RFI Geolocation Capabilities**
  - Technical, Operational and Human Factors
  - Complementary role in overall RFI Mitigation Plan

Long Term RFI Mitigation Improvements

- A lot can be done with current capabilities at reasonable cost
  - EVAIR is available now
    - *Mostly a matter of setting up interfaces and data integration*
  - ADS-B FOM Monitoring excellent example of CNS synergy use without introducing additional complexity
    - Still want to reduce guesswork in future equipment
- Next Generation MC GNSS Avionics
  - ICAO NSP requested implementation of reasonable mitigation capabilities from RTCA / EUROCAE
    - Must be careful to not impact continuity of service
  - Detection capability seen as a feasible minimum
    - Permit aircraft to switch to “A-PNT capability”
  - Information must reach ANSP
    - Quick Access Recorder, Flight Operations Quality Monitoring
    - **Future: SUR Downlink Aircraft Parameters (DAP) ??**