# Resilient Collaborative All-source Navigation with Integrity

## SET-275

## Cooperative Navigation in GNSS Degraded and Denied Environments

Maj Jonathon S. Gipson, PhD United States
Dr. Robert C. Leishman, United States

AIR FORCE INSTITUTE OF TECHNOLOGY

# The Resilient All-Source Navigation Problem

**Navigate "anytime, anywhere, using anything."**

### All-Source Navigation

With Global Navigation Satellite Systems, simultaneously redundant, synchronous measurements with provisions for integrity are readily available.

With all-source navigation, none of these are *guaranteed*.

### Integrity

A *guarantee* of navigation accuracy which includes a timely, accurate estimate of navigation error with a mechanism to provide warnings when the estimate could be untrustworthy.

### All-Source Resilience

The ability to maintain consistent all-source Fault Detection and Exclusion (FDE) and integrity operations. A *resilient* navigation framework is one that is "aware" of the sufficiency of sensor information to preserve this consistency if a sensor failure occurs. This research assumes a single simultaneous sensor failure.

# *Autonomous Resilient Management of All-source Sensors* (2018)

Jurado, Juan D., Raquet, John F., Schubert-Kabban, Christine M

<u>Resilient All-source Framework with 5 modes:</u>

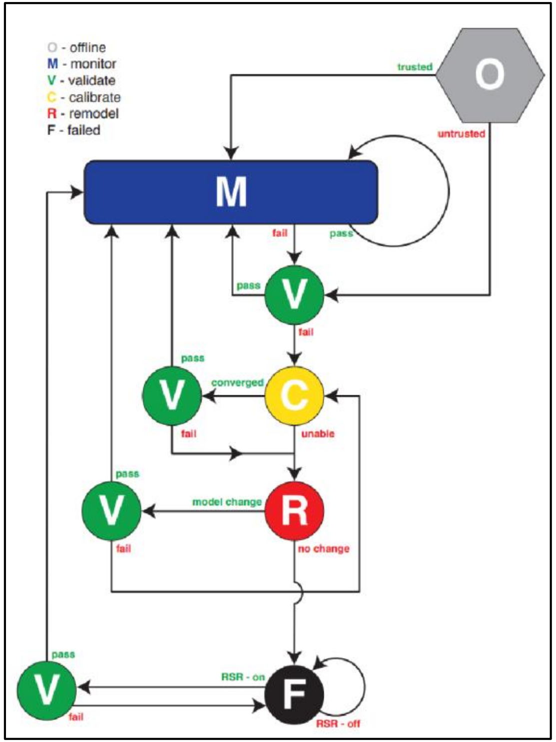
- **Offline/Failed**
- **Sensor Validation**
- **Monitoring** (SAARM)
- **Calibration**
- **Remodeling**

ARMAS uses pluggable SCORPION EKFs to address the nonlinear navigation problem:

$$\dot{\mathbf{x}}(t) = \boldsymbol{f}[\mathbf{x}(t), \boldsymbol{\epsilon}(t), \boldsymbol{u}(t), t] + \boldsymbol{G}(t)\boldsymbol{w}(t)$$

- State vector, ***x***(*N* x 1), time, ***t***
- State process model, ***f(t)***, control input vector, ***u(t)***,
- Sensor error states, $\boldsymbol{\epsilon}$ (*M* x 1)
- Linear noise operator, ***G(t)*** (*N* + *M*) x *W*
- White noise process, ***w(t)*** (*W* x 1)

Sensors are initialized as either <u>trusted</u> or <u>untrusted</u>.




<u>Figure: ARMAS State Diagram</u>

# *Sensor Agnostic All-source Residual Monitoring* (2019)

Jurado, Juan D., Raquet, John F., Schubert-Kabban, Christine M., Gipson, Jonathon S.

A T-matrix tallies the results of the tests

$$\mathbf{T}(i,j) = \begin{cases} 0, & \text{Sensor } i \text{ does not inform filter } j, \\ 0, & \chi^{*}_{[i,j]} \text{ yields } H_0 \text{ (no fault detected)}, \\ 1, & \chi^{*}_{[i,j]} \text{ yields } H_1 \text{ (fault detected)}. \end{cases}$$

Each column is summed

$$\mathbf{s}(j) = \sum_{i=1}^{I} \mathbf{T}(i,j),$$

**IF:**

1. **s** contains all zeros, **no fault detected**
2. **s** contains at least one non-zero entry, but more than one zero entry, **fault detected**
3. **s(j)** is the only zero entry in **s**, then a fault is declared, **culprit sensor identified**

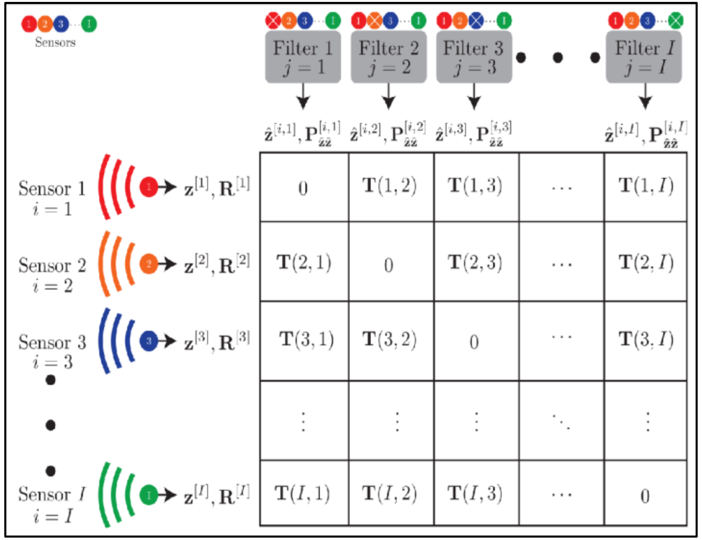



Figure: SAARM T-Matrix

**A unanimous agreement is required to determine a culprit.**

# “Layer 2” Observability Subfilter Bank

Goal: **Monitor navigation resilience.**

**Provide a timely warning when FDE and integrity assumptions are not guaranteed.**

Subfilter Inheritance Axiom:

***"If the estimation states of interest in all layer 2 subfilters are observable and stabilizable, then all layer 1 subfilters responsible for FDE and integrity operations inherit these properties.”***

Solution: *Assuming a single simultaneous sensor failure, one additional layer of subfilters is required to monitor **resilience**.*

| Layer 0 | Layer 1 | Layer 2 |
|---|---|---|
| User Output | **Fault Detection & Exclusion** | **Stable Observability Monitoring** |
| Single Main Filter | $I$ ‘choose’ 1 Unique Filters | $I$ ‘choose’ 2 Unique Filters |
| $I$ sensors | $I - 1$ sensors each | $I - 2$ sensors each |

Figure: ARMAS Configuration with Novel Observability Bank of Subfilters

Summary: **Since a subset of the “Layer 2” observability subfilters will form the new “Layer 1” subfilter bank after fault exclusion, we provide a <u>means to warn</u> the user in the event that a future single sensor failure could jeopardize the consistency of the framework.**

**<u>Result: Timely warning to notify the user to augment with offboard information.</u>**

ANT CENTER

# Stable Observability Monitoring (SOM) Overview

***The ability to maintain stable* a posteriori *estimates of system states is a primary indicator of overall estimator stability* (Ham 1983).**

- If the system model is stochastically controllable and observable, then $\mathbf{P}^+$ is **uniformly bounded from above**.
- Stabilizable states have a **unique positive-definite** $\mathbf{P}^+$.

Monitor *aposteriori* state covariance element *n* across all observability subfilters with a moving window sized to ARMAS monitoring epoch.

**Slope** and **Max Value** Thresholds:

$$O_{k,i}(n) = \begin{cases} 1, & \text{if } \mathbf{P}_j^{[\mathbf{n}]}(t_k^+) > \mathbf{P}_j^{[\mathbf{n}]}(t_{k-M}^+)\beta \\ 1, & \mathbf{P}_j^{[\mathbf{n}]}(t_k^+) > \mathbf{P}_{j,max} \\ 0, & \text{otherwise} \end{cases}$$

**Relationship between Information Filter vs Kalman Filter**

Discrete Recursive Fisher Information Filter:

$$\boldsymbol{F}(t_k^+) = \boldsymbol{\Phi}^T(t_k)\boldsymbol{F}(t_k^-)\boldsymbol{\Phi}(t_k) + \mathbf{H}^T(t_k)\mathbf{R}(t_k)^{-1}\mathbf{H}(t_k)$$

Recursive Inverse Covariance Kalman Filter:

$$\mathbf{P}(t_k^+)^{-1} = \mathbf{P}(t_k^-)^{-1} + \mathbf{H}^T(t_k)\mathbf{R}(t_k)^{-1}\mathbf{H}(t_k).$$

User sets $\mathbf{P}_{j,max}$ as a maximum **static** $P(t_k^+)^{[n]}$ allowable.
User sets $\boldsymbol{\beta}$ as a tuning parameter for acceptable **transient** $P(t_k^+)^{[n]}$ growth allowable.

$$SOM_{AddNewSensor} = \begin{cases} true, & \text{if } \sum_{n=1}^{N} O_k(n) > 0 \\ false, & \text{otherwise} \end{cases}$$

If any observability layer subfilter exceeds the **slope** or **max value** threshold, *warn* user to *augment* with **offboard information**.

**SOM monitors the stability of *aposteriori* system state estimates in the observability layer to provide an assessment of the signal/noise ratio supplied to system states.**

# Split “Stingy” Collaboration

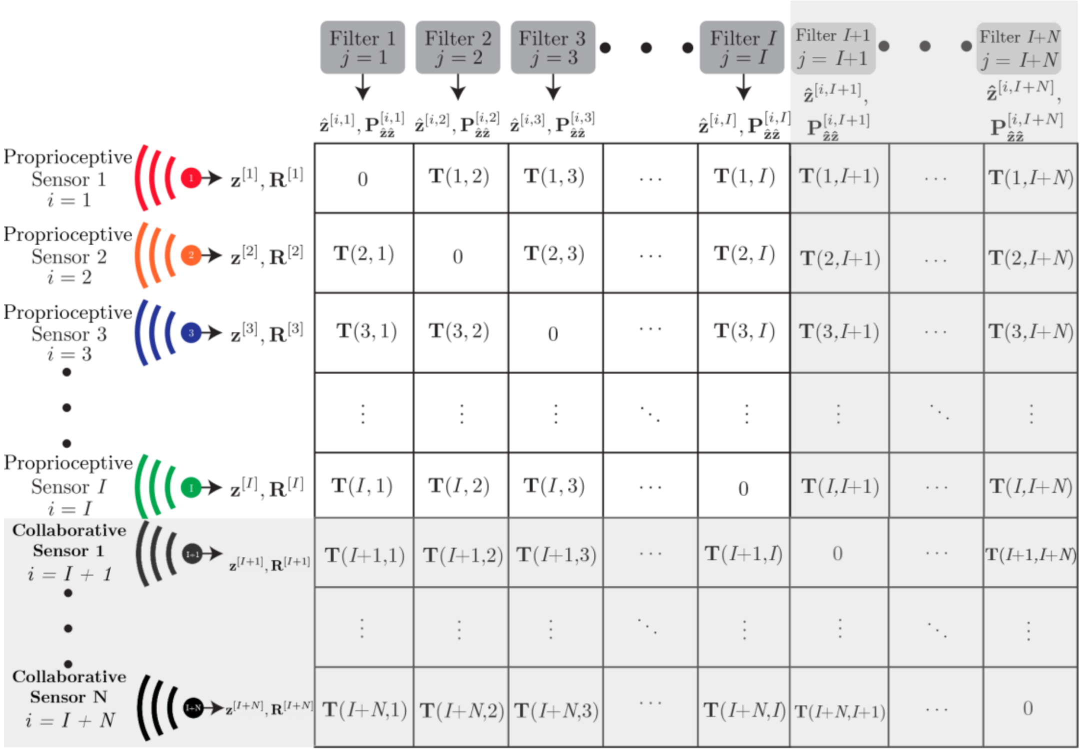



Figure: Collaborative ARMAS-SOM T-Matrix

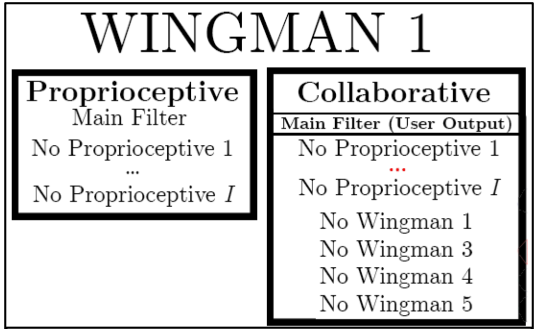



Figure: Split ARMAS-SOM Configuration

**Collaborative information (gray) is used to augment proprioceptive information (white).**

**This forms the T-matrix structure for the collaborative all-source framework which is fused into a single main filter for user output.**

# Stingy Collaboration Example: WNG3 Corruption

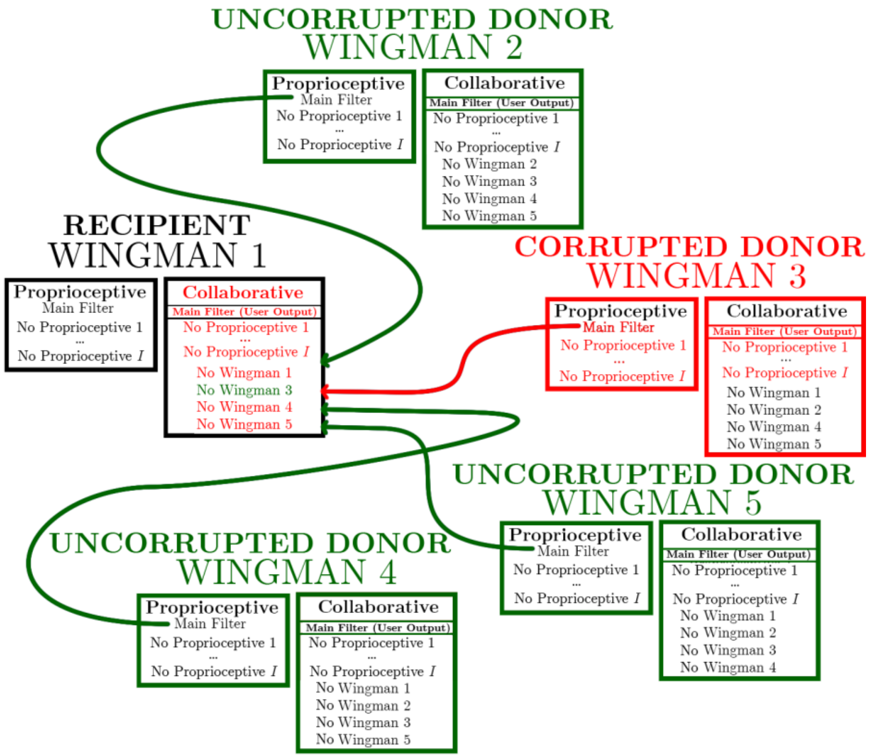



**Figure: Wingman 1 receives corrupted collaborative donor information from Wingman 3.**

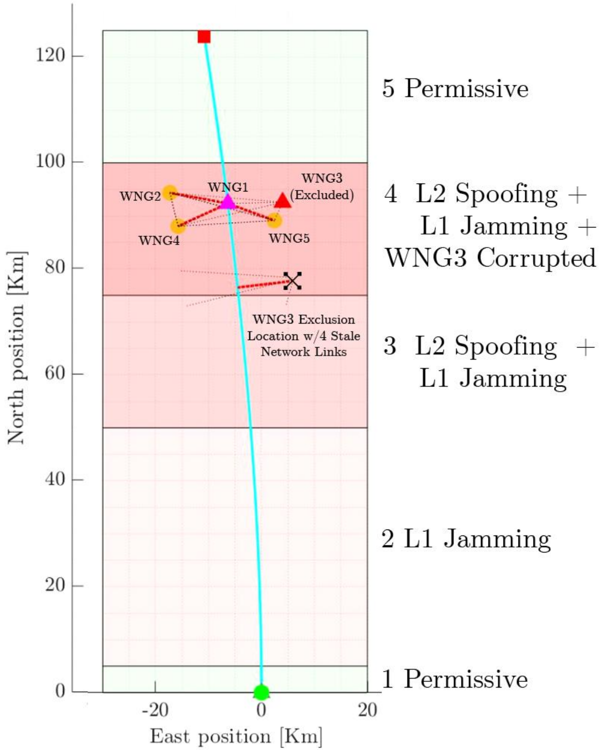



**Figure: Wingmen independently exclude Wingman 3 and regain consistency**

# NAVWAR Simulation Introduction

Proprioceptive Position Est.

Collaborative Position Est.

Collaborative Subfilter Position Est.

Collaborative Subfilter Covariance Est.

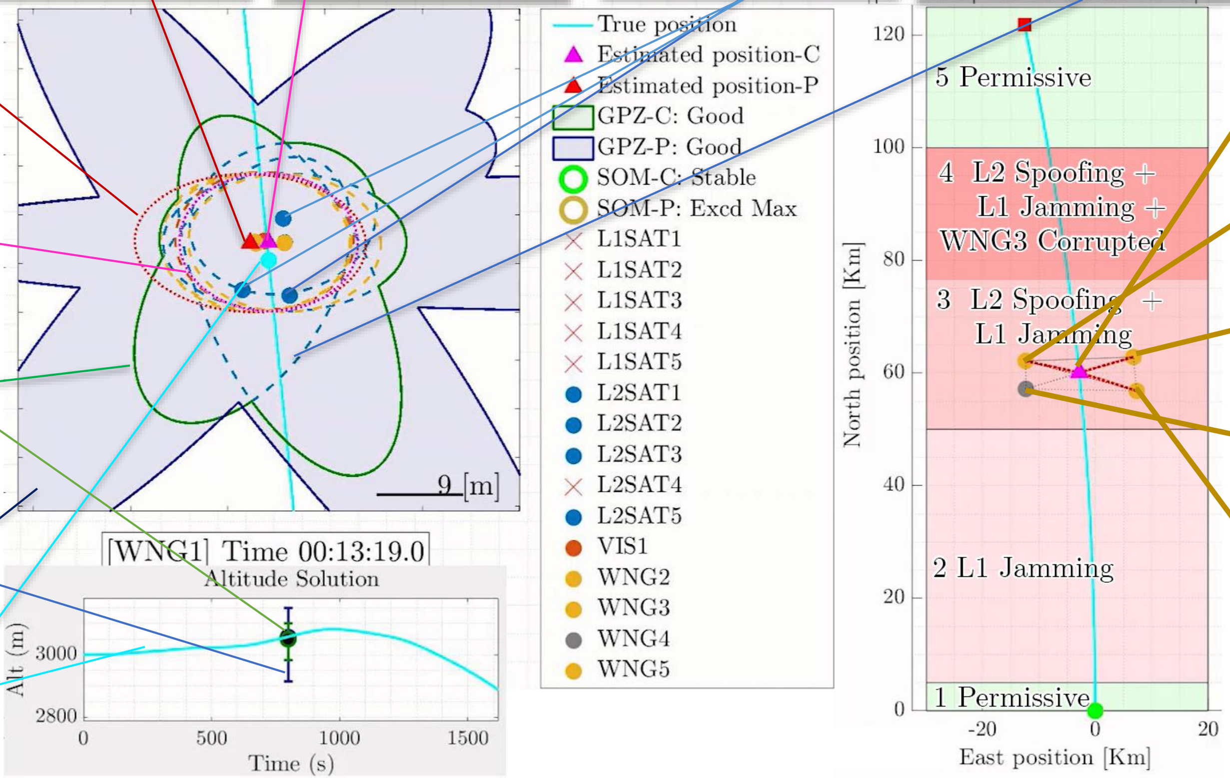
Proprioceptive Main Filter Position Covariance Est.

Collaborative Main Filter Position Covariance Est.

Collaborative GPZ

Proprioceptive GPZ

Truth




WNG1

WNG2

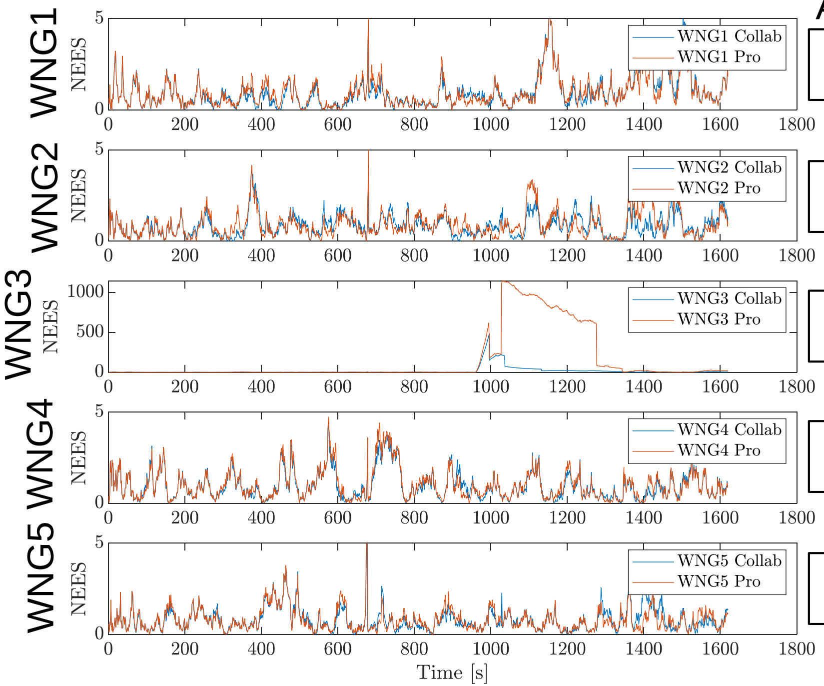
WNG3

WNG4

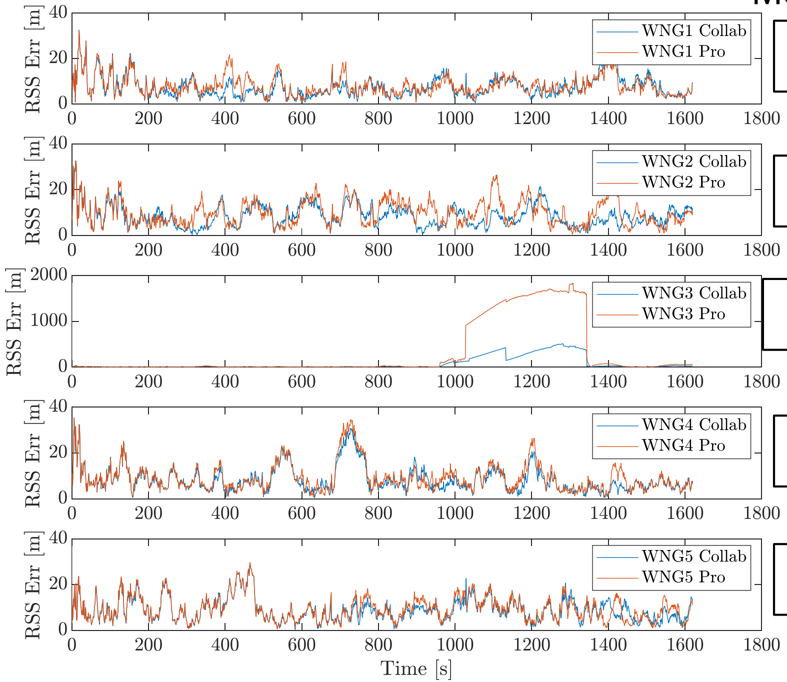
WNG5

# Collaborative Nav L1 Jam/L2 Spoof/Recovery (VIDEO)

# Summary of NAVWAR Resilience Demo




| ANEES | Collab | Pro |
|---|---|---|
| WNG1 | 0.99 | 0.98 |
| WNG2 | 0.86 | 0.92 |
| WNG3 | 16.08 | 147.22 |
| WNG4 | 0.97 | 1.01 |
| WNG5 | 0.80 | 0.80 |




| Mean RSS | Collab | Pro |
|---|---|---|
| WNG1 | 7.50 m | 8.10 m |
| WNG2 | 8.45 m | 9.93 m |
| WNG3 | 77.98 m | 307.25 m |
| WNG4 | 8.30 m | 9.23 m |
| WNG5 | 8.94 m | 9.38 m |

Figure: NEES for Parallel Collaborative and Autonomous ‘Proprioceptive’ ARMAS-SOM instances.

Figure: 3-D RSS Error for Parallel Collaborative and Autonomous ‘Proprioceptive’ ARMAS-SOM instances.

WNG1 Collaborative All-Source: **80% time resilient**  WNG1 Proprioceptive All-Source: **25% time resilient**