The Dimensions of RFI

…and how ngVLA is being designed to accommodate them

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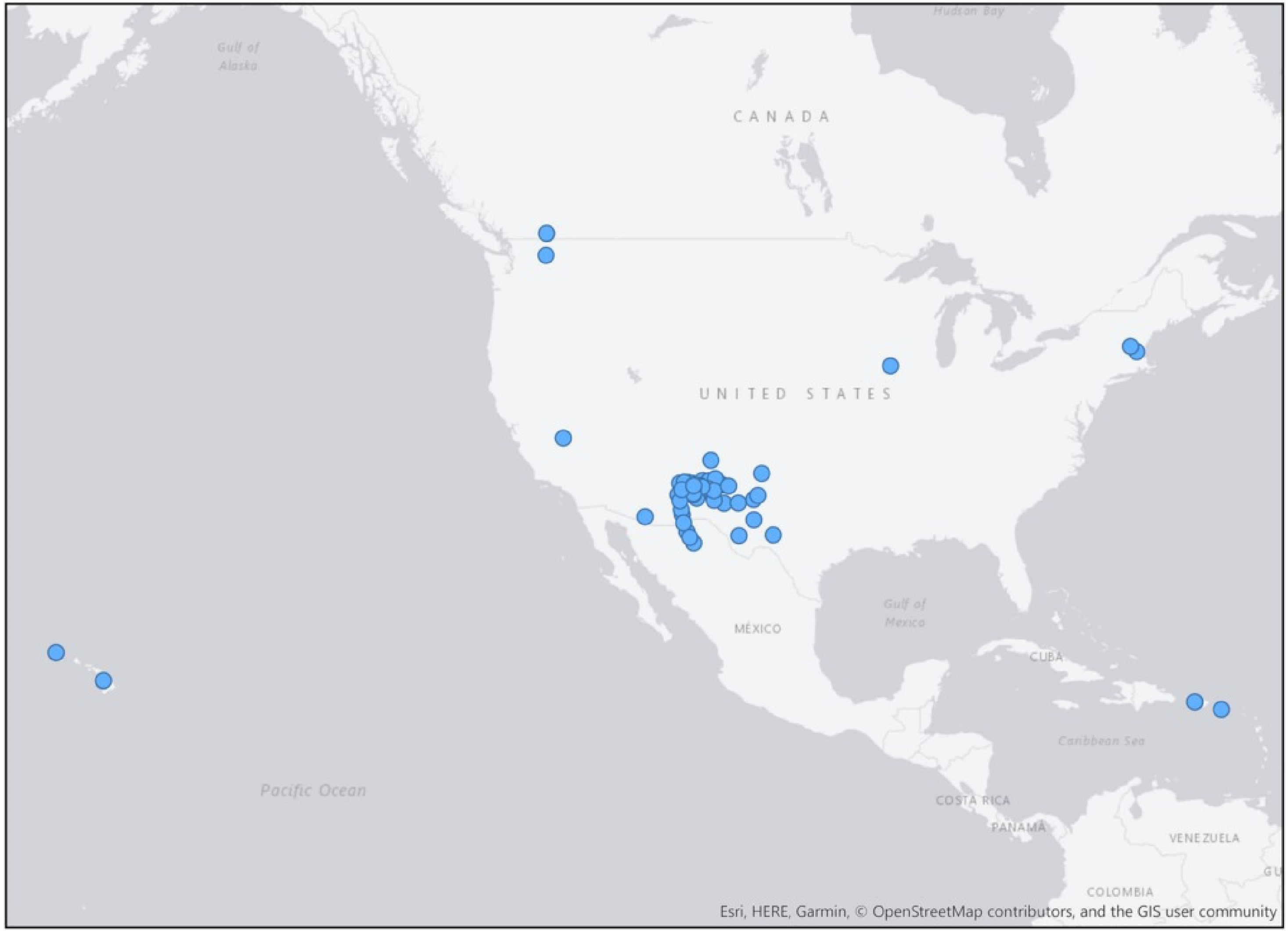
ngVLA overview

- 214 main antennas, 18m
- 30 long-baseline antennas , VLBA++
- 1.2 – 116 GHz
- Water vapor radiometer (18 – 26 GHz) on each antenna


Hudson Bay
Gulf of Alaska
CANADA
UNITED STATES
Gulf of Mexico
MÉXICO
CUBA
Caribbean Sea
Pacific Ocean
COSTA RICA
PANAMA
VENEZUELA
COLOMBIA
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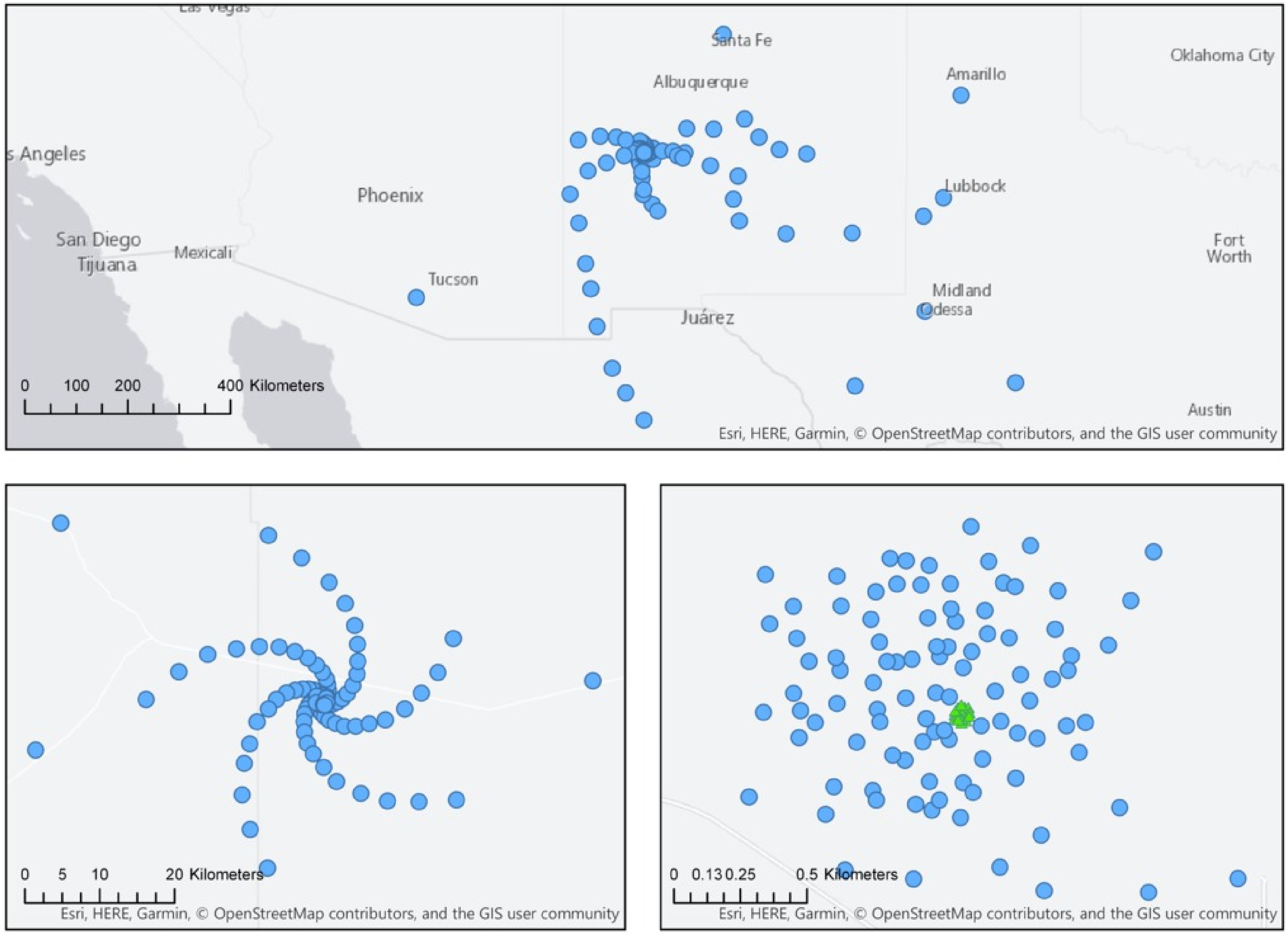

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ngVLA status

- Reference design published, all material publicly available at https://ngvla.nrao.edu
- Conceptual Design period through 2020
- Astro2020 results mid-2021

RFI Goals

- Create foundations for ngVLA and other instruments before we even know what algorithms we need
- Allow RFI research to be performed on a live telescope
- Ensure new techniques can be incorporated with minimal impact
- Adapt to changing RFI with minimal impact
- “Minimal impact” == “few or no architectural changes”

Time

Domain	Scale	
time	ps – ns	raw samples
pre-integration	ms	pre-integration
post-integration	s	post-integration

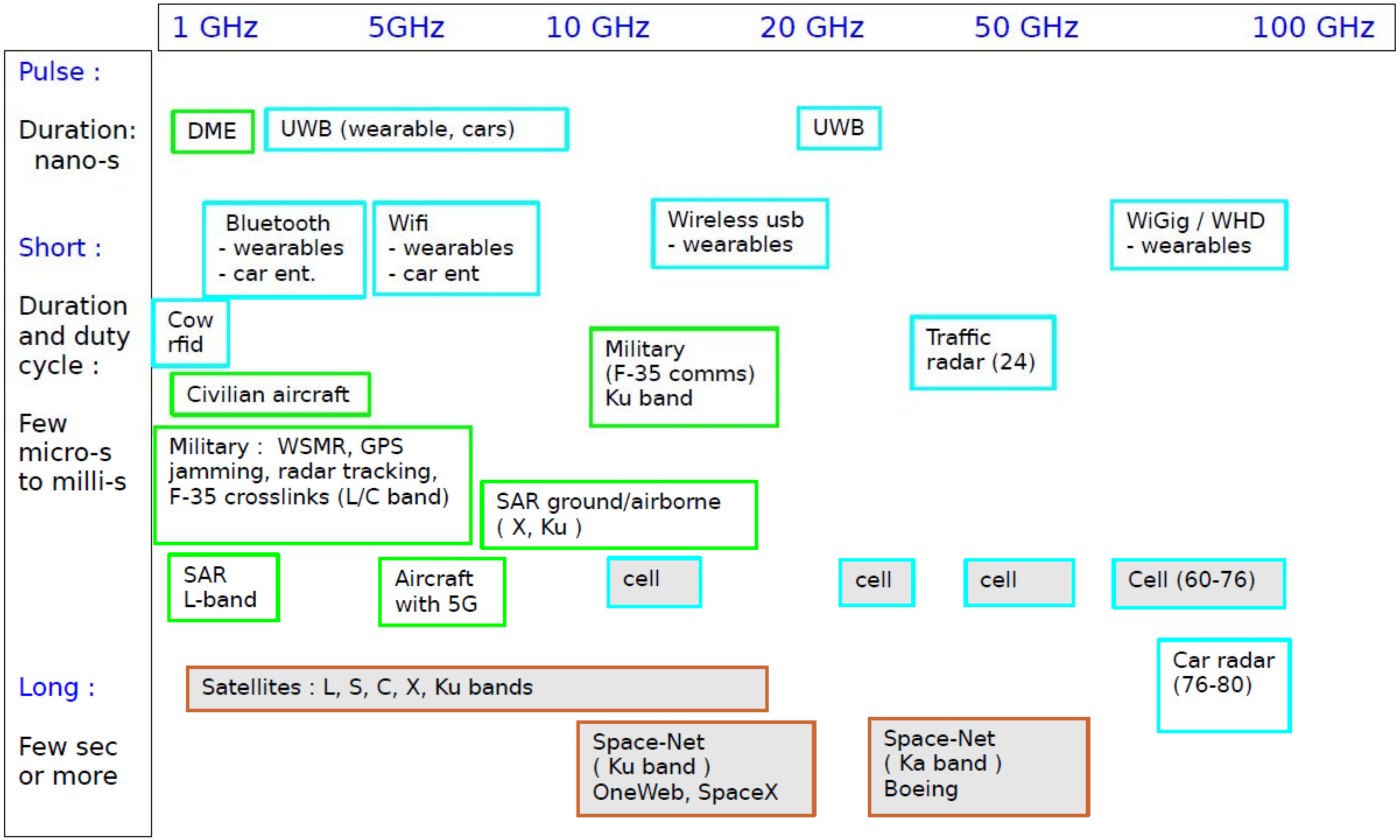
Frequency

Domain	Scale	
Receiver	1 – 50 GHz	Analog electronics
Digitizer	1 – 10 GHz	Digitized bandwidth in a receiver
Window	1 – 100 MHz	Range of frequencies within digitized bandwidth
Channel	Hz - MHz	Smallest frequency quantum for instrument/observation

Location

Domain	
Antenna	Affects single antennas at any one time
Group	Affects a group of antennas
Array	Affects most of the array simultaneously

Future RFI Landscape (1-100 GHz)



1 GHz 5GHz 10 GHz 20 GHz 50 GHz 100 GHz

Pulse :

Duration: nano-s

DME

UWB (wearable, cars)

UWB

Short :

Duration and duty cycle :

Few micro-s to milli-s

Bluetooth
- wearables
- car ent.

Wifi
- wearables
- car ent

Wireless usb
- wearables

WiGig / WHD
- wearables

Cow rfid

Military (F-35 comms) Ku band

Traffic radar (24)

Civilian aircraft

Military : WSMR, GPS jamming, radar tracking, F-35 crosslinks (L/C band)

SAR ground/airborne (X, Ku)

SAR L-band

Aircraft with 5G

cell

cell

cell

Cell (60-76)

Car radar (76-80)

Long :

Few sec or more

Satellites : L, S, C, X, Ku bands

Space-Net (Ku band) OneWeb, SpaceX

Space-Net (Ka band) Boeing

Color : Local RFI (~ few antennas) RFI on large fraction of array(airborne) RFI on entire array (satellite)

Shading : White : Seen for a small fraction of observing time. Grey : Seen for most/all observations

Prediction

Domain	
Forecast	• scheduled occurrence • predictable, e.g. orbit parameters • notification by service, agency, or partner • all timescales – microseconds to decades
Non-forecast	• not predicted • unannounced • modified schedule, e.g. orbit change • repeating but asynchronous, e.g. radar

- Requires prior knowledge, i.e. RFI database
- Likely requires external databases, e.g. orbital parameters

Character

Domain	
Fingerprinted	• matches known characteristics in the set of domains relevant to this RFI • likely non-Boolean
Non-fingerprinted	• does not match a known set of characteristics

- Requires prior knowledge, e.g. RFI database
- Database could be shared to distribute our workload!

Summary: domains

Time	time, pre-integration, post-integration
Location	antenna, group, array
Prediction	forecast, non-forecast
Character	fingerprinted – non-fingerprinted

- Observations will also have partitioning – these are just for RFI

Examples

RFI	Data	Frequency	Location	Prediction	Character
meteorological radar	t, pre	window	group	no	yes
commercial satellite	pre, post	channels	group, array	yes	yes
cell tower	pre, post	channels	antenna, group	no	yes
vehicle radar - nearby	pre, post	receiver	antenna, group	no	yes
vehicle radar - distant	t, pre	channels	antenna, group	no	yes
new dark satellite	pre, post	window	array	no	no
drone, advance notice	pre	channels		yes	partial

Why domains?

- Map domains to RFI sources
- Classify RFI handler code by domains
- Assume: more individual RFI producers than domain groups
- Minimize the number of RFI lines of code
- A handler that fits a domain can have settings that fine-tune it to fit many RFI sources with similar domains

RFI code entities

- Detector
  - Detects without impacting science data
  - Can produce its own datastreams, e.g. science metadata, notifications, modified science data
- Excisor
  - Modifies science datastream to reduce RFI impact
  - Can also have non-science datastreams

Trigger

- Prediction or detection of an RFI (automatic or manual)
- External notification of RFI impending/disappearing
- Prediction or detection of RFI disappearance
- Observational settings change, calculate new RFI impact

Action

- Re-evaluate observation schedule
- Create or configure entities
- Enable/disable entities
- Send notification to entities
- Send metadata
- Trigger RFI evaluation
- Update RFI database
- Capture raw data

Strategy

- Tree of detectors, excisors, others e.g. logic (e.g. behavior tree)
- Inputs include:
  - Observation properties
  - RFI databases
  - Triggers
- Outputs include:
  - Structure of entities
  - Connections of entities to data sources
  - Connections of entities to entities
  - Entity configurations
  - Logging/saving

Strategy

- Multiple RFI sources will likely be present in a given observation
- Partitioning by domain will not always allow isolation of RFI sources
- So RFI system must be capable of handling multiple simultaneous RFIs
- Invasive mitigation (excision) will leave a footprint in data
- Sequence of excisors will affect the net footprint
- Strategy is a potentially complex sequence of operations
- Strategy creation should be very flexible to handle complex threats

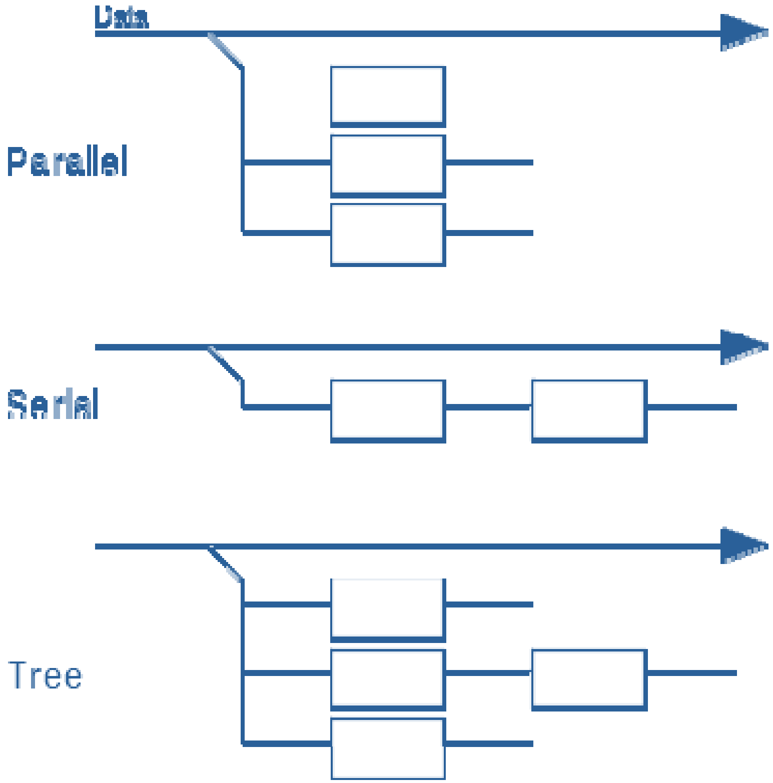
Strategizer

- Creates tree of handlers, hooks up comms, specifies settings
- Fault trees, simulated annealing, genetic algorithm, ML
- Should be able to run on archived data
- Implies capability to archive partial data from every domain (t, pre in addition to post) for research
- Strategies proven successful should be recorded in DB along with source RFI characteristics so expensive strategizer algorithms are rarely needed in realtime
- A strategizer run could be scheduled dynamically when new RFI is detected interfering with current observation

Detector Considerations

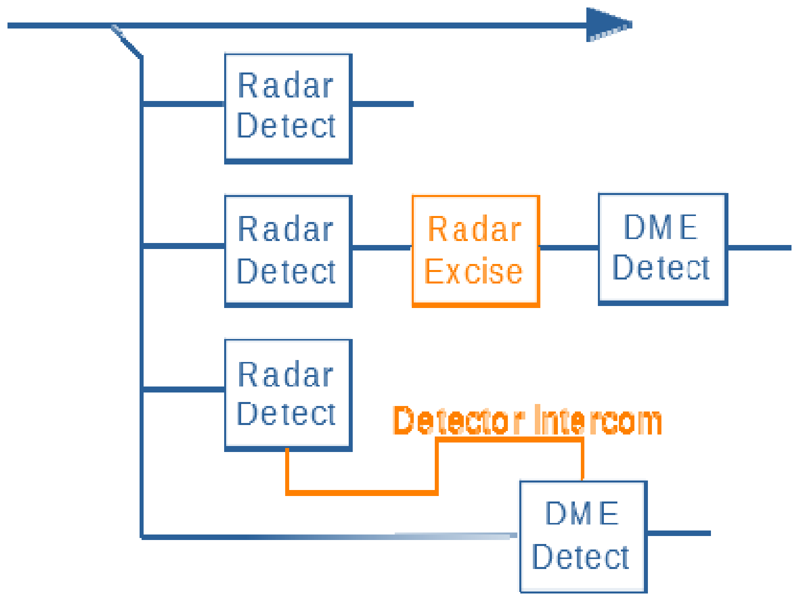
- Detectors must have small false-positive and false-negative
- Some RFI fingerprints are nicely orthogonal (radar vs. QAM)
- These detectors could be placed in parallel
- Some RFI fingerprints are *not* going to be orthogonal (radar vs. DME)
- These detectors may have to be placed in series so they can progressively modify data

Detector Configurations



- Tree allows parallel, serial, or combinations
- If implement as behavior tree, can incorporate logic

Dependent Detectors



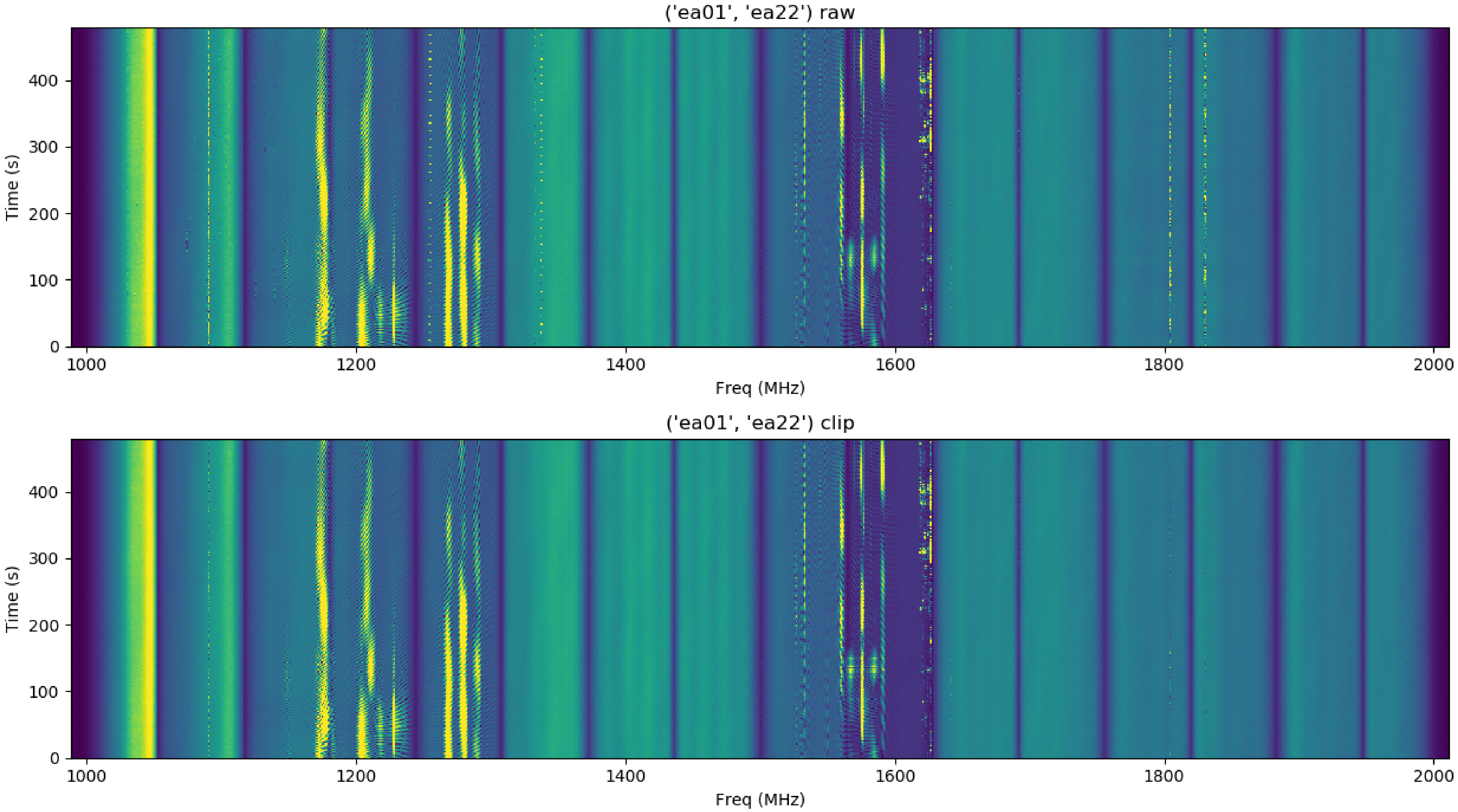
- Excisors could be placed between detectors
- Intercom between detectors

Detector Reporting

- In domains higher than archive speed, likely use aggregator to report to archive, e.g.:
  - number of voltage samples excised
  - residuals for subspace excision
- Note: can report at higher speeds over intercom to other entities

VLA WIDAR example

- Trigger on voltage threshold
- Excise samples in t domain
- Blanks definable time (e.g. 10us) to zeros
- Aggregation: reports number of valid samples in integration period
- Example works well on some oulses, less well on others
- Tuning parameters could likely work very well on other pulse systems


('ea01', 'ea22') raw
Time (s)
0
100
200
300
400
1000
1200
1400
1600
1800
2000
Freq (MHz)
('ea01', 'ea22') clip
Time (s)
0
100
200
300
400
1000
1200
1400
1600
1800
2000
Freq (MHz)

When to detect RFI?

- Instantiate all known detector trees and run all in parallel?
- Special detector trees for unknown RFI?
- Associate detector trees with observation parameters, and just instantiate those detector trees for current observation?
- When do we run strategizer:
  - always?
  - when new RFI detected in realtime?
  - every new observation?
  - periodically?

Summary

- Map RFI sources to domains
- Classify detectors and excisors according to the domains
- Anticipate or detect affected domains for observation
- Create strategies to deal with RFI present
- Let strategies take actions as configured
- Develop and incorporate new detectors, excisors without architectural change
- We’ll put all our work on github as we get it working

Flagging is Failure

- If we have to throw away collected data, we’ve wasted resources
- bug could be in:
  - observation parameters: setup failed to avoid known RFI
  - observation scheduler: did not schedule around anticipated RFI
  - RFI database: did not characterize RFI [properly]
  - external: unknown fingerprint
  - external: unknown schedule
  - management: did not allocate time to perform necessary RFI research
- counts against telescope MTBF/uptime
- ounce of prevention, pound of cure
- management wedge for researching and maintaining RFI mitigation