RFI Mitigation for the ngVLA – a cost-benefit analysis

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RFI mitigation for the ngVLA

(1) RFI Landscape

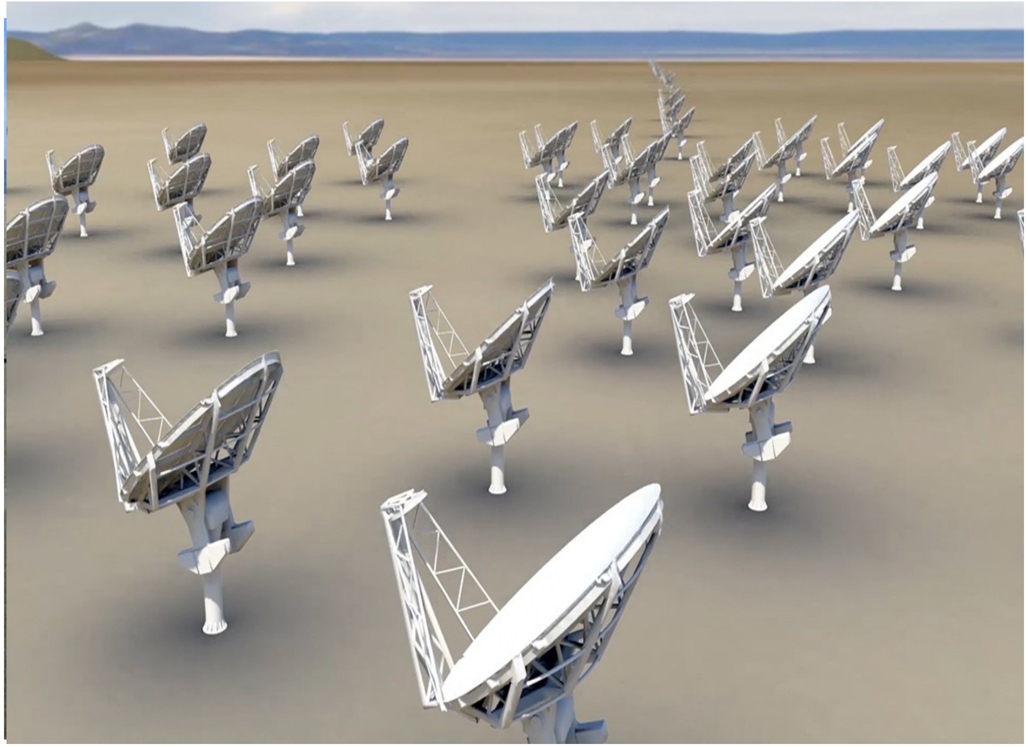
(2) Mitigation approaches integrated with real-time-system design

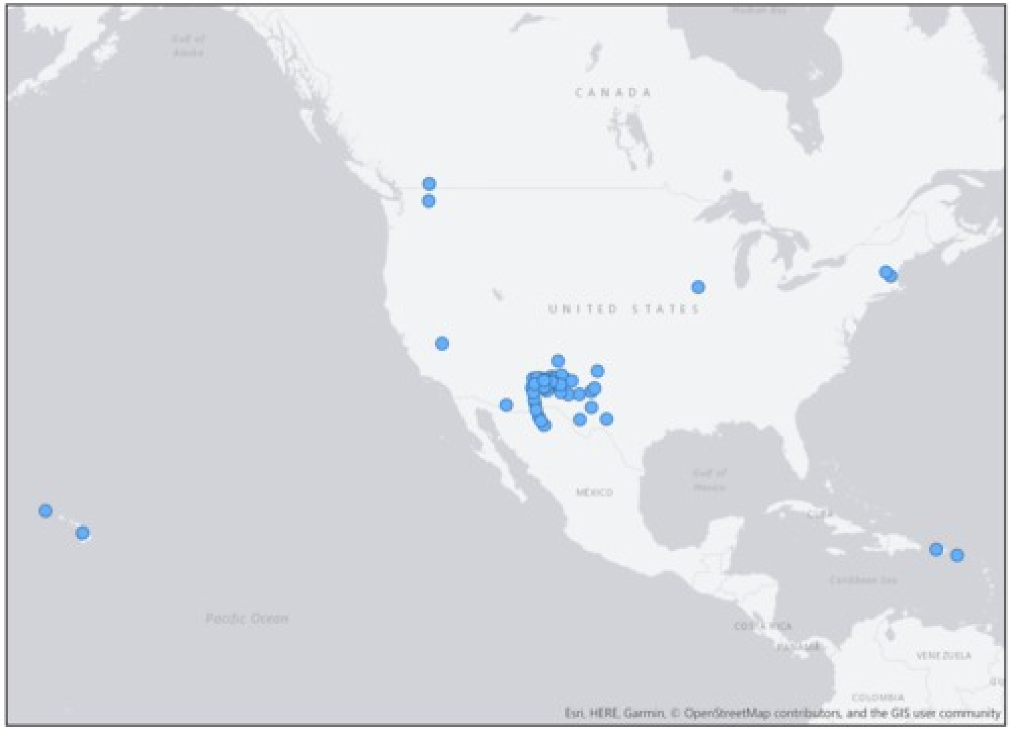
(3) A cost benefit analysis

(4) Prototype focus areas

Details : ngVLA Memos #48, #71, #70

Next Generation VLA (2030+ if funded)





NGVLA

263 dishes (18m and 6m)

1.2 – 116 GHz, in 6 bands (except 50-70 GHz)

Fixed configuration : ~50m to 8000km baselines

Location : In/around New Mexico + VLBA sites

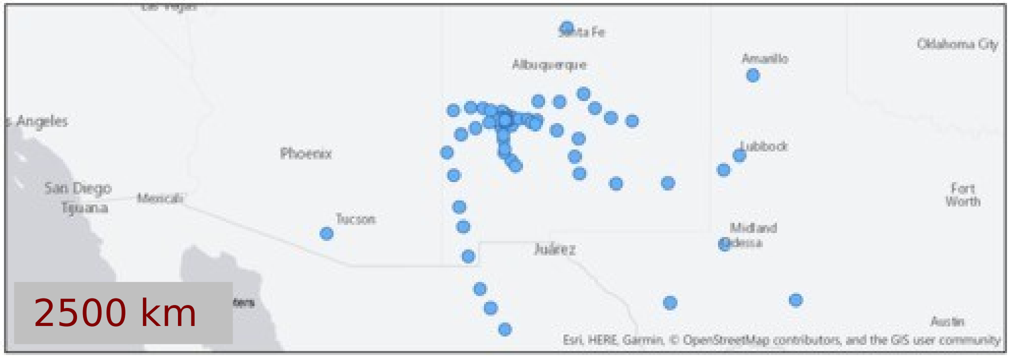
Purpose :

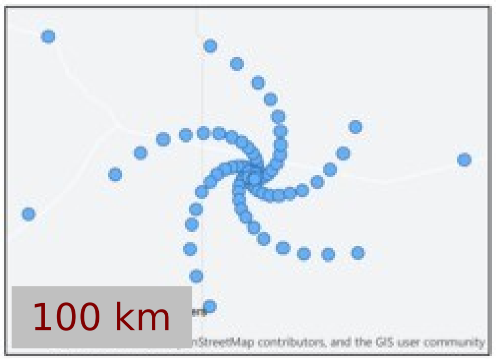
- 10x improvement in imaging sensitivity and resolution (compared to VLA)

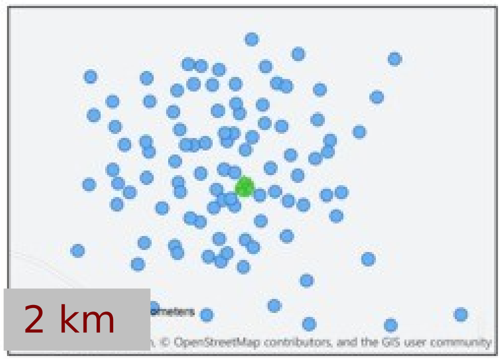
- Bridge the gap between current VLA and ALMA frequencies

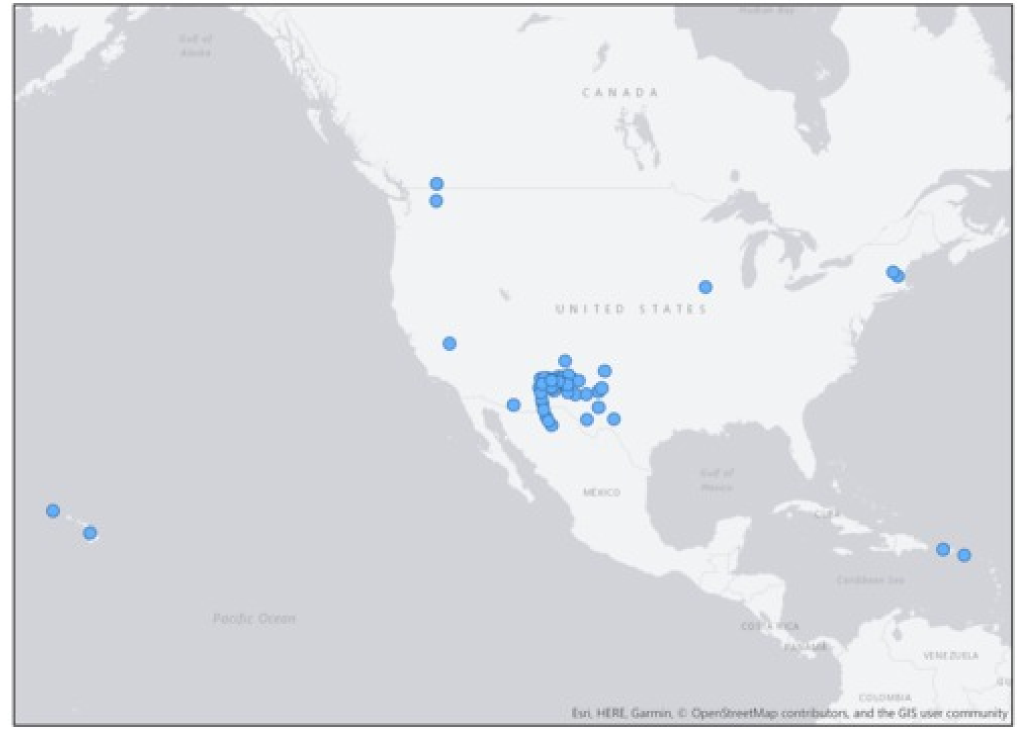
  - New Science

Next Generation VLA









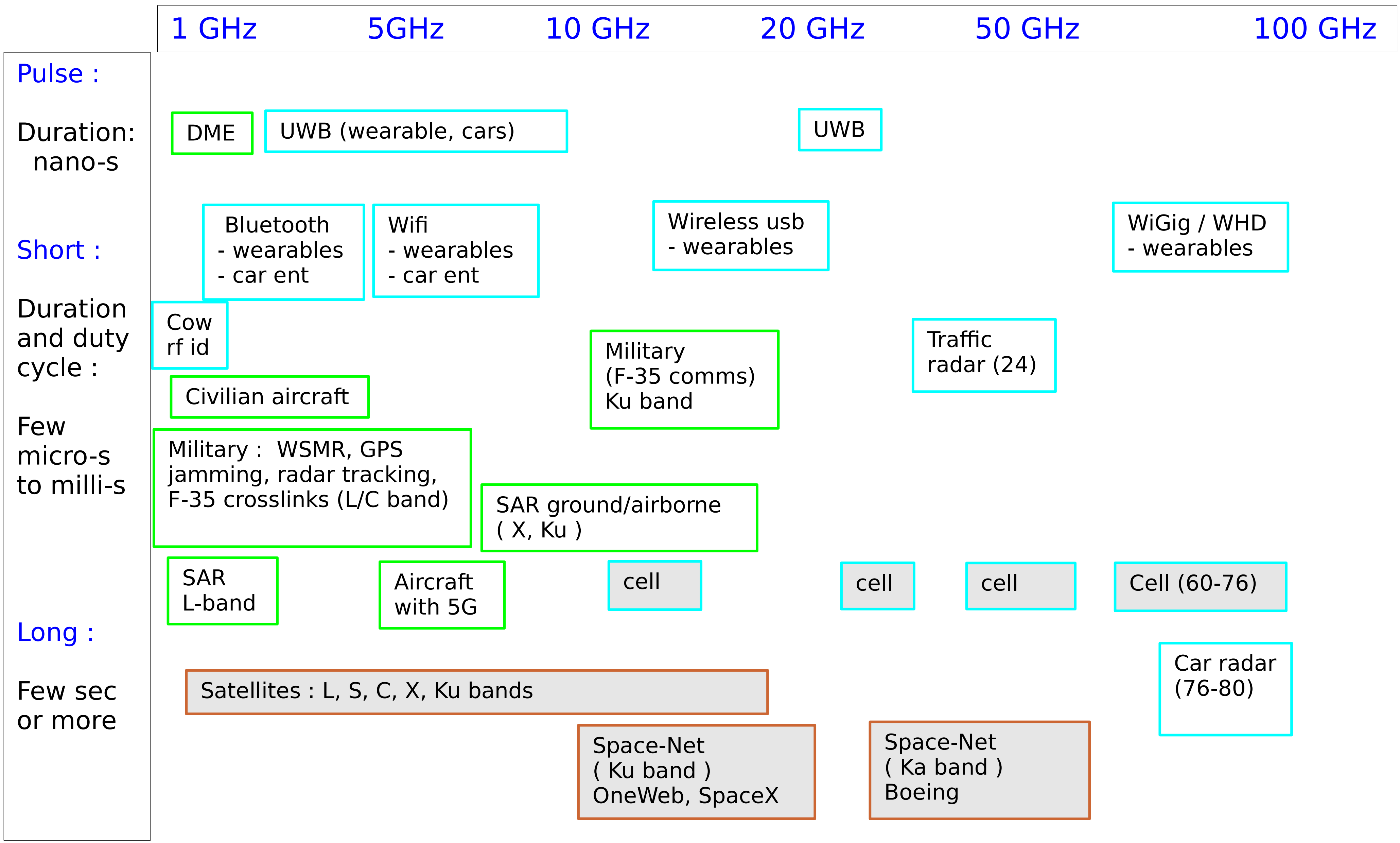
Frequency range : 1.2 – 116 GHz

Main Core : 100 x 18m dishes (< 2km baselines)
Plains Spiral : 114 x 18m dishes (< 70 km baselines)
Compact core : 19 x 6m dishes (< 0.1 km baselines)
Long Baselines : 30 x 18m dishes (100 – 8000 km baselines)

Main/Compact Cores (119) : Plains of San Augustin (remote)

Other antennas (144) : Near humans. All antennas (263) : Will see satellites

Future RFI Landscape (1-100 GHz) [ngVLA Memo #48]



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

Impact of RFI : Current and Future

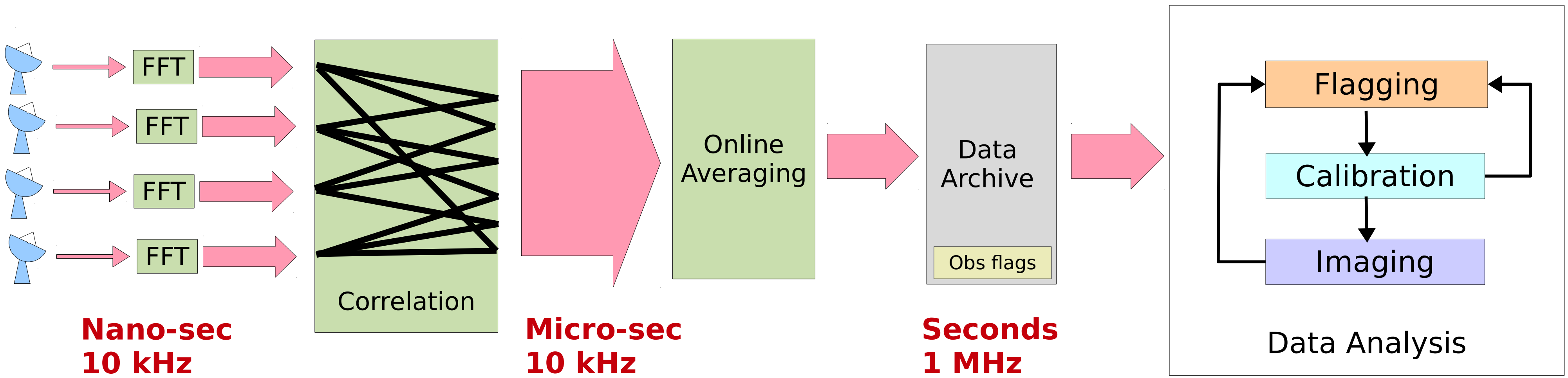
Present :

- Continuum Science : RFI-free gaps with extra observing time
- Spectral Lines Science : Lost if RFI is present
- Time Domain Science : Many false positives

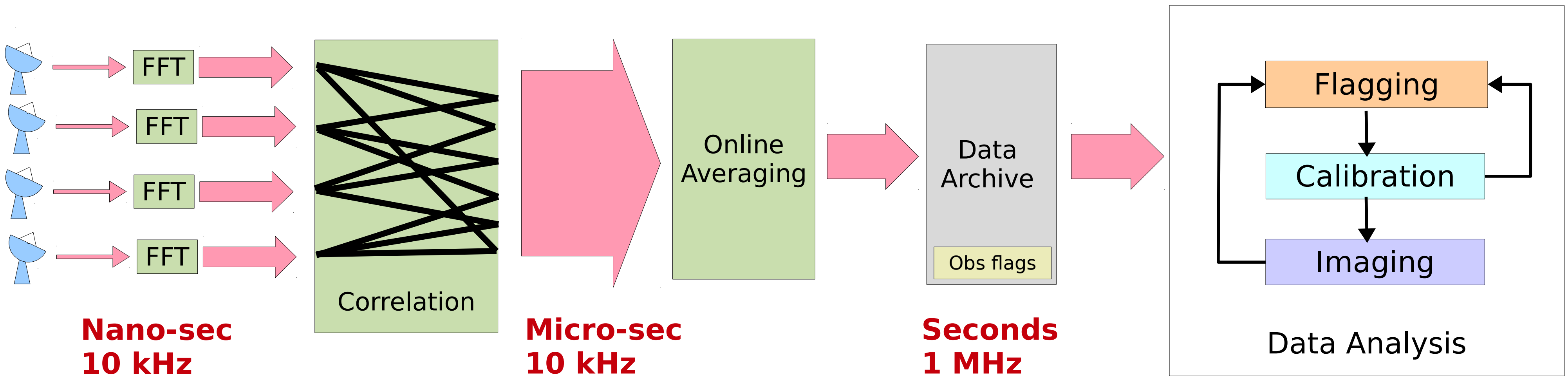
NgVLA Key Science Goals	Frequency Coverage
KSG1: Unveiling the Formation of Solar System Analogs on Terrestrial Scales	20-110 GHz, ang.res < 0.01”, 0.5 uJy/bm, highest possible bandwidth
KSG2: Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry	16-50 GHz
KSG3: Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present	Spectral lines between Band 4 (20.5-27.5GHz) And Band6 (91-116 GHz)
KSG4: Using Pulsars in the Galactic Center to Make a Fundamental Test of Gravity	3-30 GHz
KSG5: Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy	1-2 GHz, 5-20 GHz, 1-3.5 GHz, 20-34 GHz

Significant overlap with known RFI bands (ngVLA Memo #48)

Data acquisition and analysis



Data acquisition and analysis



Problems :

- At 1sec, 1 MHz resolutions, intermittent RFI appears continuous

  => We are throwing away good data

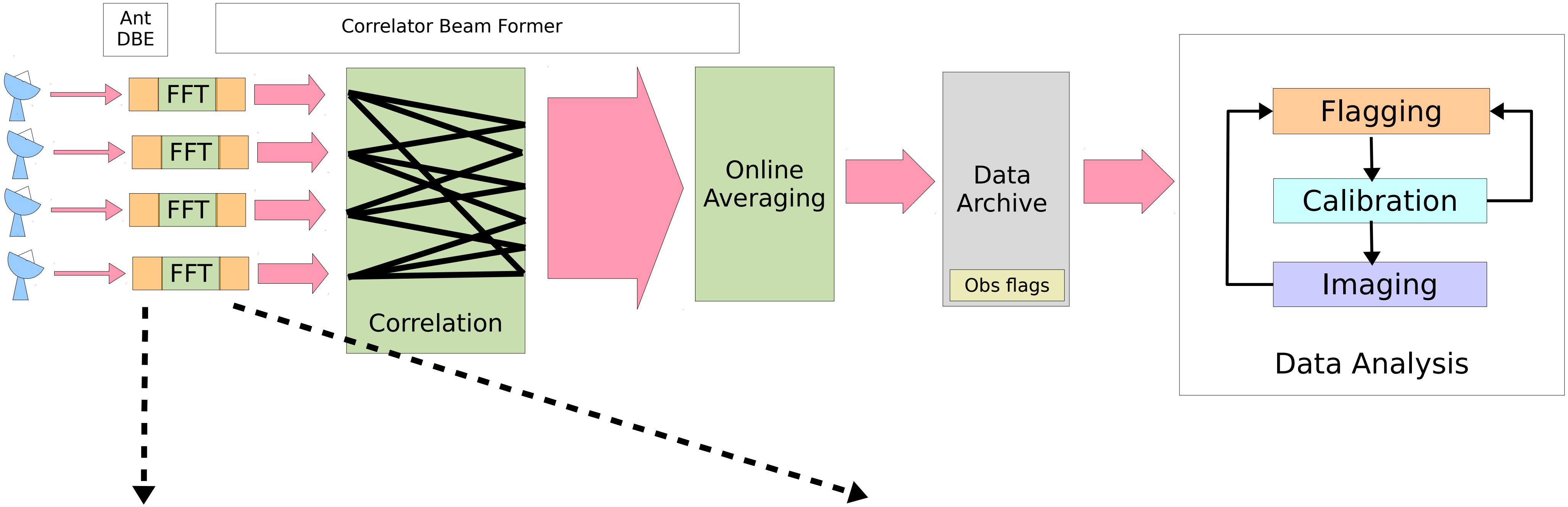
- Satellite RFI is partially decorrelated at 1sec, 1 MHz resolutions

  => Cannot model the signals well enough to subtract them

- No interaction between scheduling and post-processing or science needs

  => Not making use of what we learn.

Real-time RFI mitigation before correlation



Outlier detection on time-series.

Detect and mask nano-second pulses seen by individual antennas

RFI : Sparks, UWB transmissions

Action : Drop Samples, Gather metadata

Design : Additional FPGA-compute resources
Transport of flags and RFI samples

Outlier detection on real-time spectrum

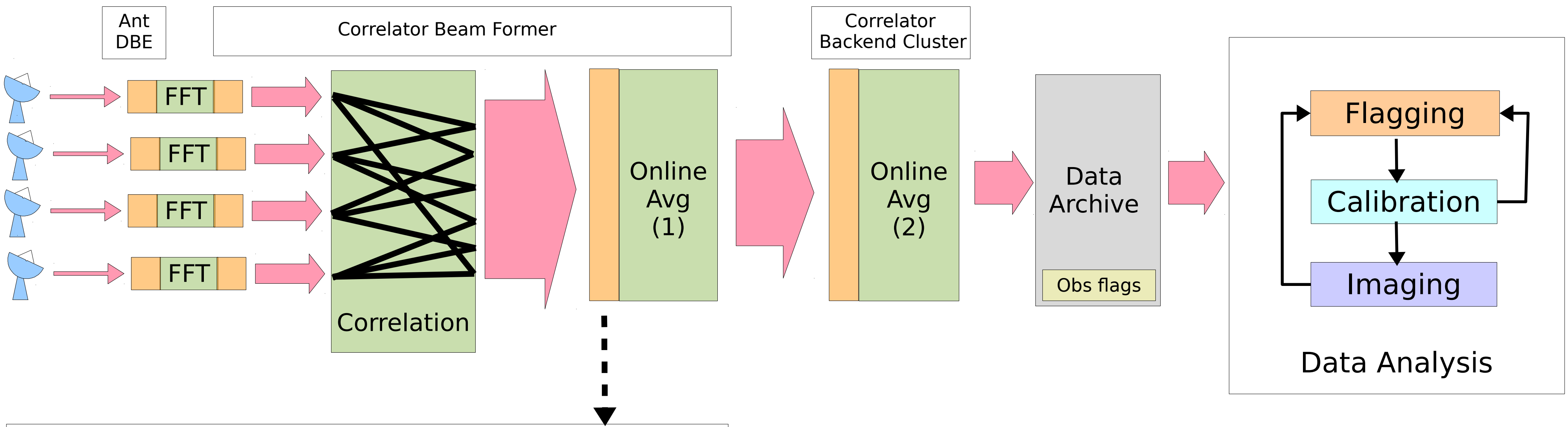
Detect and mask/label corrupted channels per antenna

RFI : Any strong narrow-band signal

Action : Mask samples
Label samples
Gather metadata

Design : Additional FPGA-compute resources
between the F and X steps
Transport of flags and RFI samples

Real-time RFI mitigation after correlation



Automatic flagging on visibilities
(1 micro-sec – 1 milli-sec, 10-100 KHz)

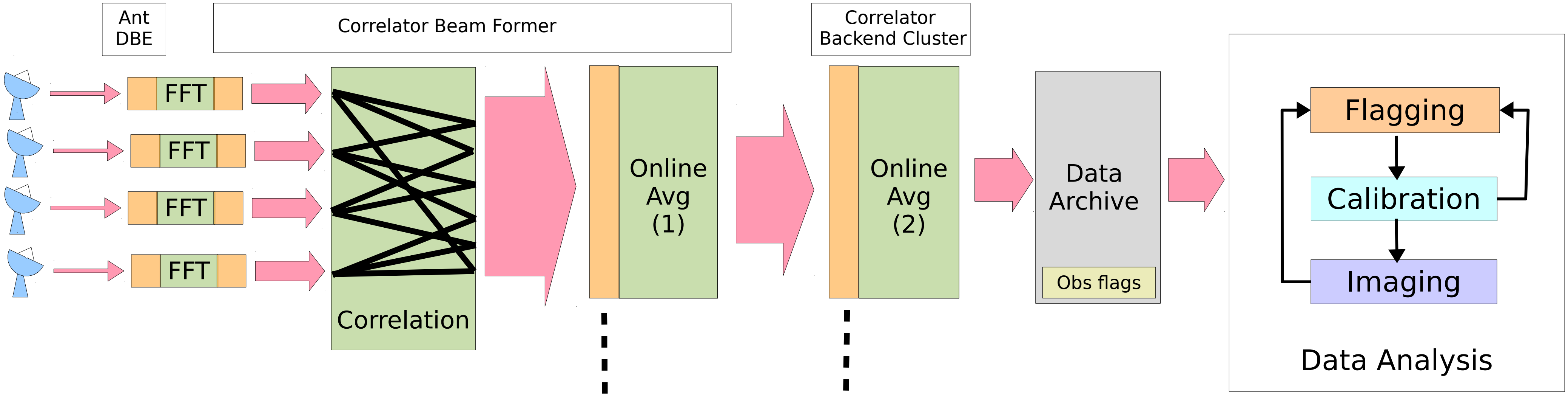
Detect and mask correlated RFI in the baseline x time x frequency (3D) cube

RFI : Intermittent communication signals
- Duty cycles of 10s of micro-sec
- Channel width of 100 KHz.

Action : Drop samples during averaging
Record correct weights

Design : Additional FPGA resources
Transport of flags and weights
Flexible averaging timescales
Raw and modified streams

Real-time RFI mitigation after correlation



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Action : Drop samples during averaging
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Design : Additional FPGA resources
Transport of flags and weights
Flexible averaging timescales
Raw and modified streams

Interference modeling and subtraction
(10 milli-sec, 10 kHz : no/partial decorrelation for ngvla core)

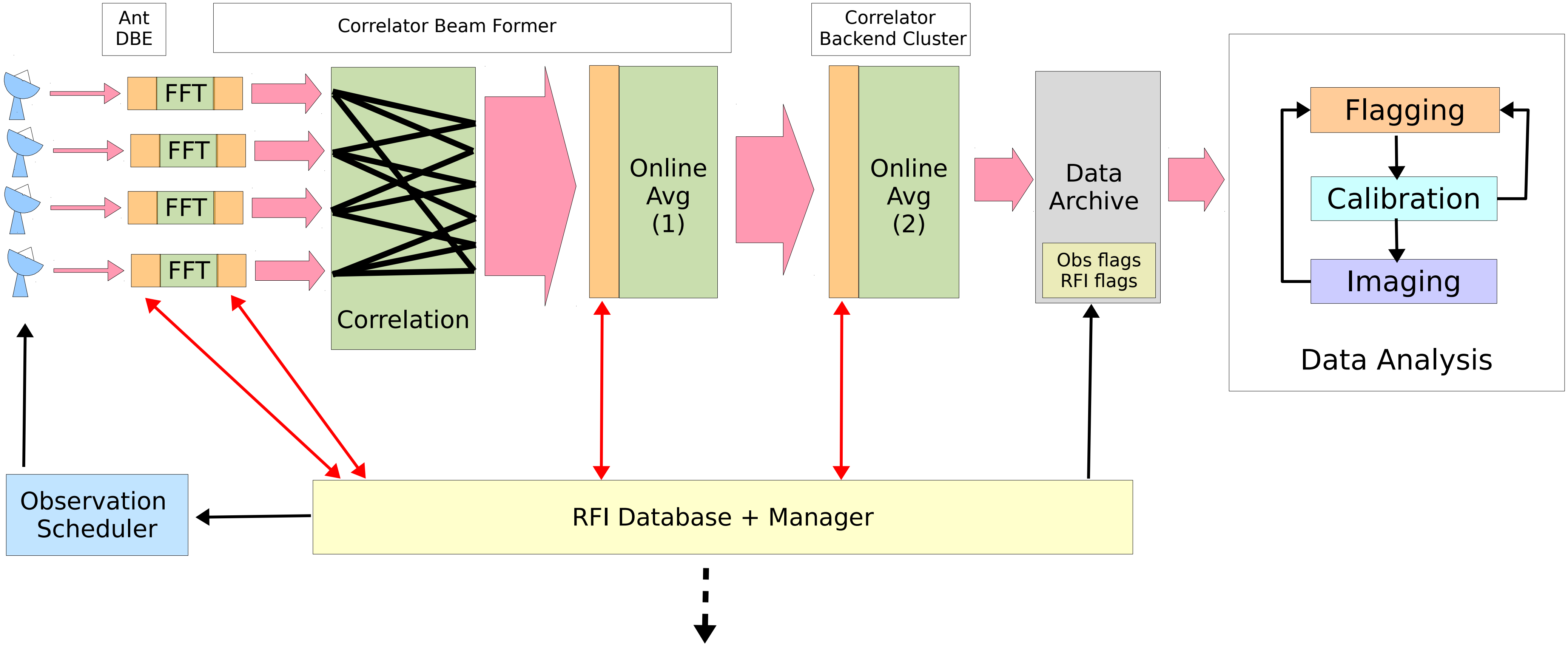
Subspace projection. *Real-time all-sky Imaging.* Source location. Ddcal + Peeling.

RFI : Continuous data transfer signals
- Cell 5G, Airborne 5G
- Satellite Radio / Internet

Action : Subtract out the RFI signal
Modify weights

Design : Off-the-shelf cluster sized for real-time modeling/subtraction algorithms
Raw and modified streams, flags/wts

RFI Database and Manager



Database : Store RFI characteristics and meta-data

- Known satellite orbits and frequencies, locations / schedules of terrestrial emitters,
- Meta-data about RFI detected by the real-time system

Manager : Analyse RFI metadata and decide optimal actions for the current observation.

- Record RFI information in the archive (expected as well as observed)
- Match the current RFI and observing goals to suitable mitigation algorithms and tunings
- Smart scheduling around predictable (or currently detected) emitters

How practical are these ideas ?

Balance the cost of such real-time systems with how useful they may be.

- How effective are RFI mitigation algorithms in data recovery ?
- Will the saved observing time or science be worth the operating/dev cost ?
- How stable will design decisions be with varying RFI characteristics ?
- Is there any preferred system specification, or should flexibility be the key ?
- What areas need algorithm/system R&D ?
- At what (streaming) data rates can we run the appropriate algorithms ?

  - What ideas to focus on for prototyping and design ?

=> A cost benefit analysis (Fermi estimation, Back-of-envelope-calc, Experience + common sense, etc....)

Cost-Benefit Analysis

Factors :

- RFI types and characteristics (time, frequency, space)
- Algorithm options and expected efficacy (outlier detectors, model/subtract)
- Data Processing Stages (time/freq resolution at which the data are viewed)

---- Match algorithms to the RFI type and data processing stage.

Metrics :

- Fraction of data loss, for different mitigation options and data resolutions.
- Extra observing time required to compensate (when possible).
- Compute cost of running chosen algorithms at the optimal data resolution

RFI Characteristics

RFI Parameters :

Key	Description	Example
type	Type of RFI signal	Cell 5G
freqrange	Allocated Frequencies (GHz)	[1.427,1.518],[3.3,3.8],[5.15,5.925],[24.25,27.5],[31.8,33.4],[37.0,43.5],[45.5,50.2],[50.4,52.6],[66.0,76.0],[81.0,86.0]]
freqres	Channel width of the signal (kHz)	200.0
timeres	Time resolution of signal (Sec)	1e-03 (millisec packets)
timegap	Time between signals (sec)	0.0 (continuous when on)
timefrac	Fraction of a day that signals are on	[1.0, 0.2, 0.1]
arrayfrac	Subset of array that sees the RFI	[outlier, core, full]

Array :

- outlier : 30 long-base + 20 spiral : upto 1000 km : near humans
- core : 119 antennas : upto 1km : remote area
- full : 263 antennas : upto 1000 km : will see airborne RFI

RFI Type : People, UWB/UWBcar, Cell 5G, LEO Sat, Aircraft Comm, Sat Comm.

Data Processing Options

(A) Antenna-based real-time flagging :

Time res : 1 ns, 10 ns

Algorithm : 1D filters

(B) Baseline based high time resolution flagging :

Time res : 10 us, 100 us, 1 ms, 10 ms
Chan res : 100 kHz
(assuming gaps in RFI transmissions)

Algorithm : Autoflag

(C) High time resolution modeling and subtraction :

Time res : 10 us, 100 us, 1 ms, 10 ms
Chan res : 10 kHz
(feasible only for ngVLA core)

Algorithm : Subspace Projection
Calibration+Imaging
DD-cal+Peeling

(D) Post processing flagging

Time res : 0.1 s, 1s, 10s
Chan res : 1 MHz

Algorithm : Autoflag

Estimating data loss fractions

Fraction of data loss $= \dfrac{nbase_{rfi}}{nbase_{total}} \times \dfrac{hours\ per\ day}{24} \times \dfrac{max\left(t_{sig}, t_{data}\right)}{t_{sig} + t_{gap}}$

=> Filling factor is lowest when data_res matches sig_res.
=> Filling factor is 1.0 when data_res > (sig_res + sig_gap)

- Calculate fraction of data loss for each RFI type and data processing stage
- Pick the best option (of processing stage and RFI algorithm).

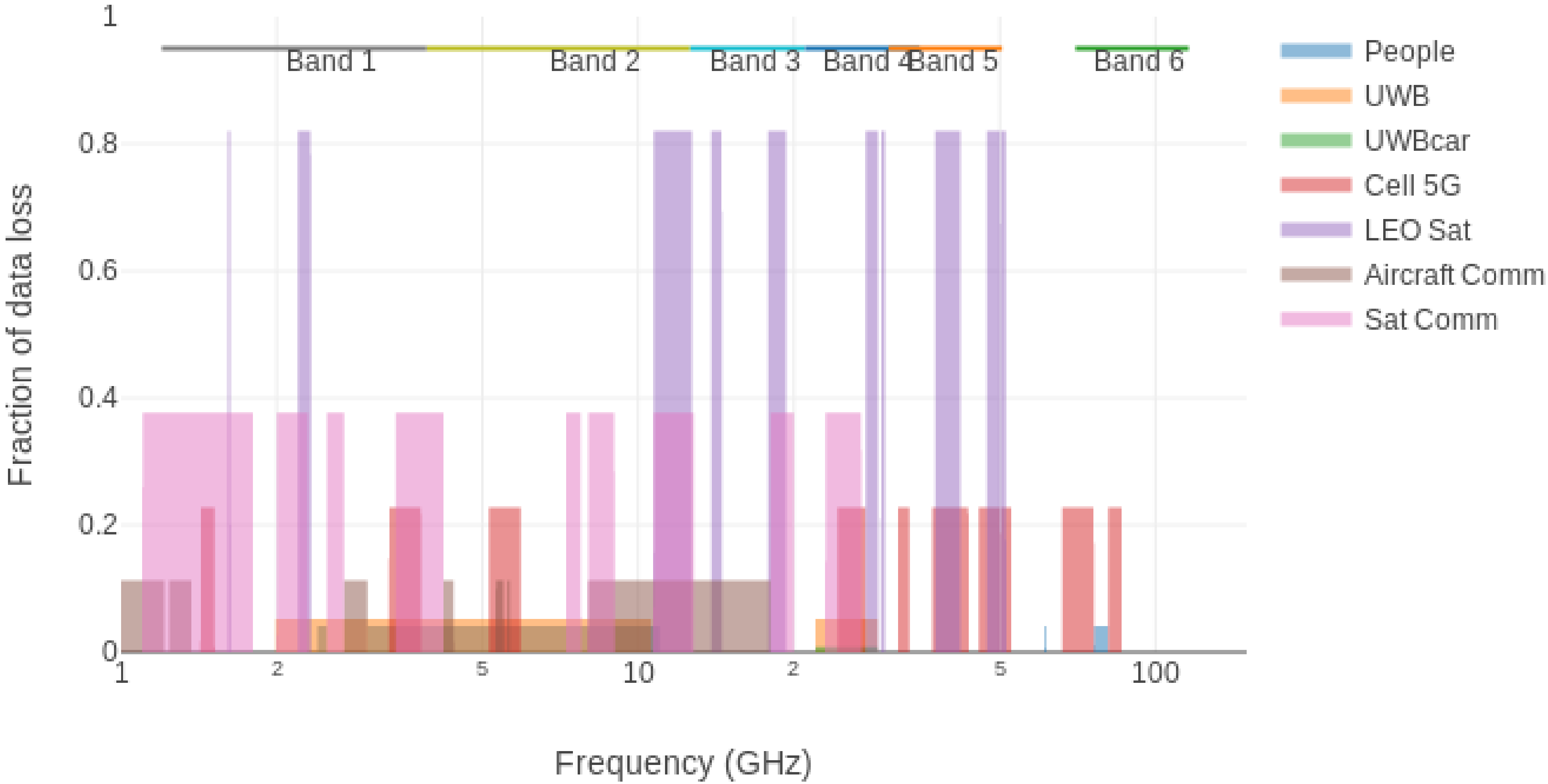
Decorrelation : The $sinc\left(\phi\right)$ attenuation, with a threshold to decide whether the RFI has fully decorrelated or is present. (included in nbase_rfi)

- Parameterized by angular distance from phase center and target imaging dynamic range.

Calculate upper and lower bounds for overall data loss per frequency :

- All RFI types overlap in the data
- All RFI types touch different subsets of the data

Estimated data loss – only post-processing

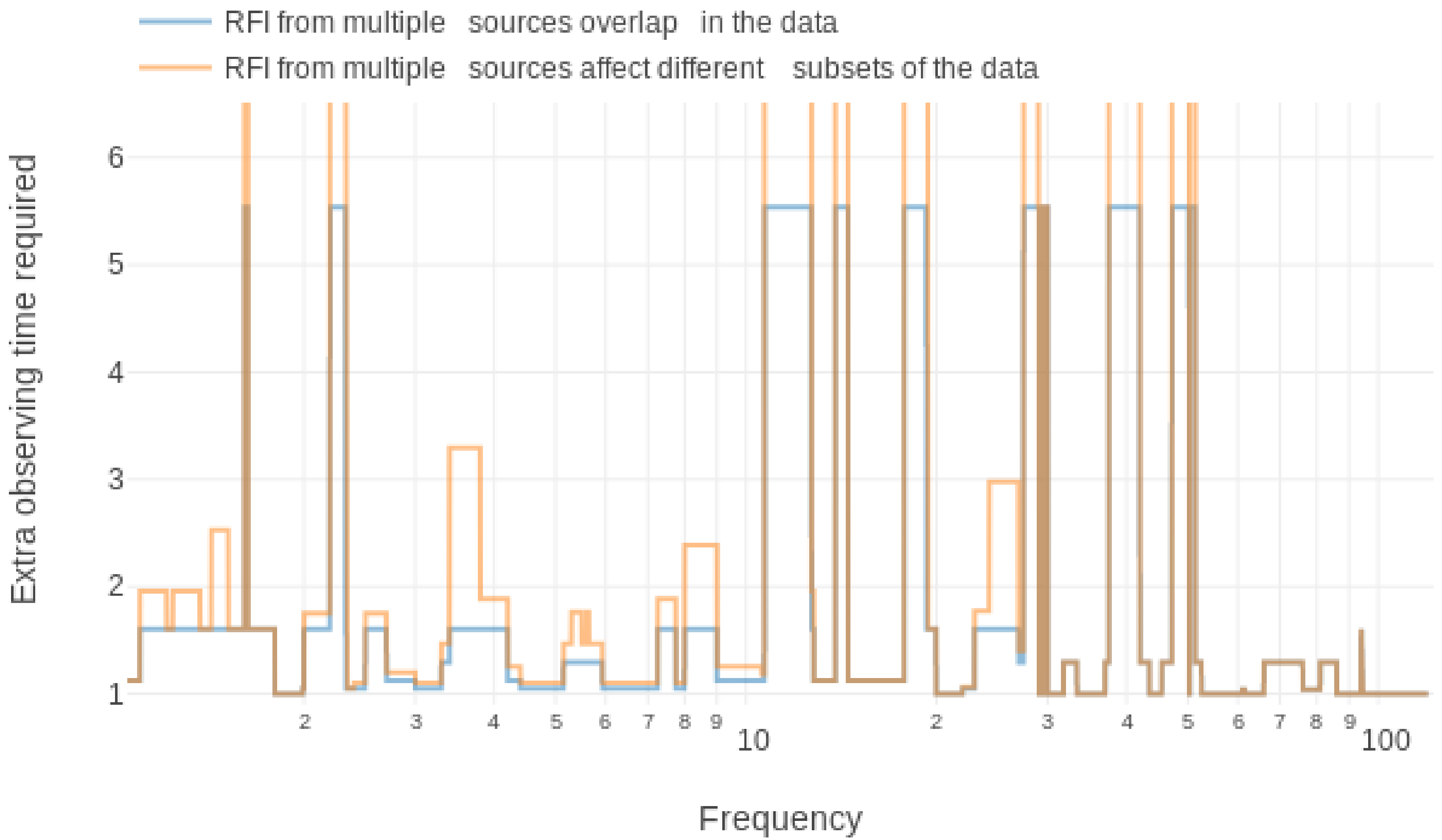


Assumptions : Multiple RFI types with different footprints in frequency, time, and antennas.
Entire allocated band is filled (i.e. no usable gaps in freq), no spillover/saturation

Calculations : Fraction of affected baselines, effects of RFI decorrelation and uncorrelated RFI
RFI filling fraction (signal duty-cycle vs data resolution), overlapping vs disjoint RFI

RFI mitigation : Only post-processing flagging

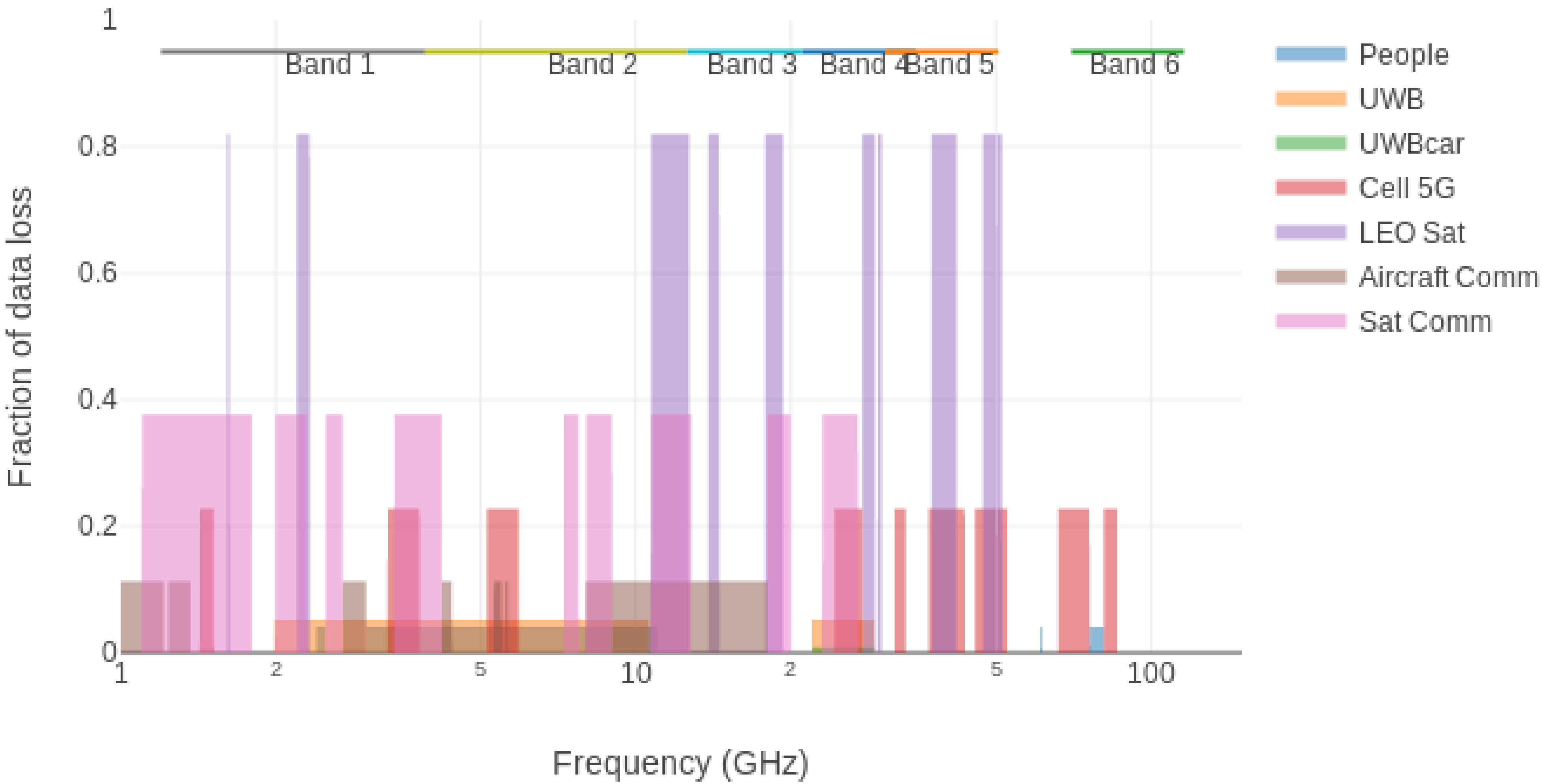
Estimated extra observing time required – status quo



Calculation : Extra observing time (relative to RFI-free data) is equal to the fraction of data lost, accounting for a similar loss fraction on the extra time as well.

Analysis : Continuum science can be derived from RFI-free (or low-RFI) frequency ranges.
Spectral line science is lost in bands with more than 50% data loss (practically...)

Estimated data loss – only post-processing

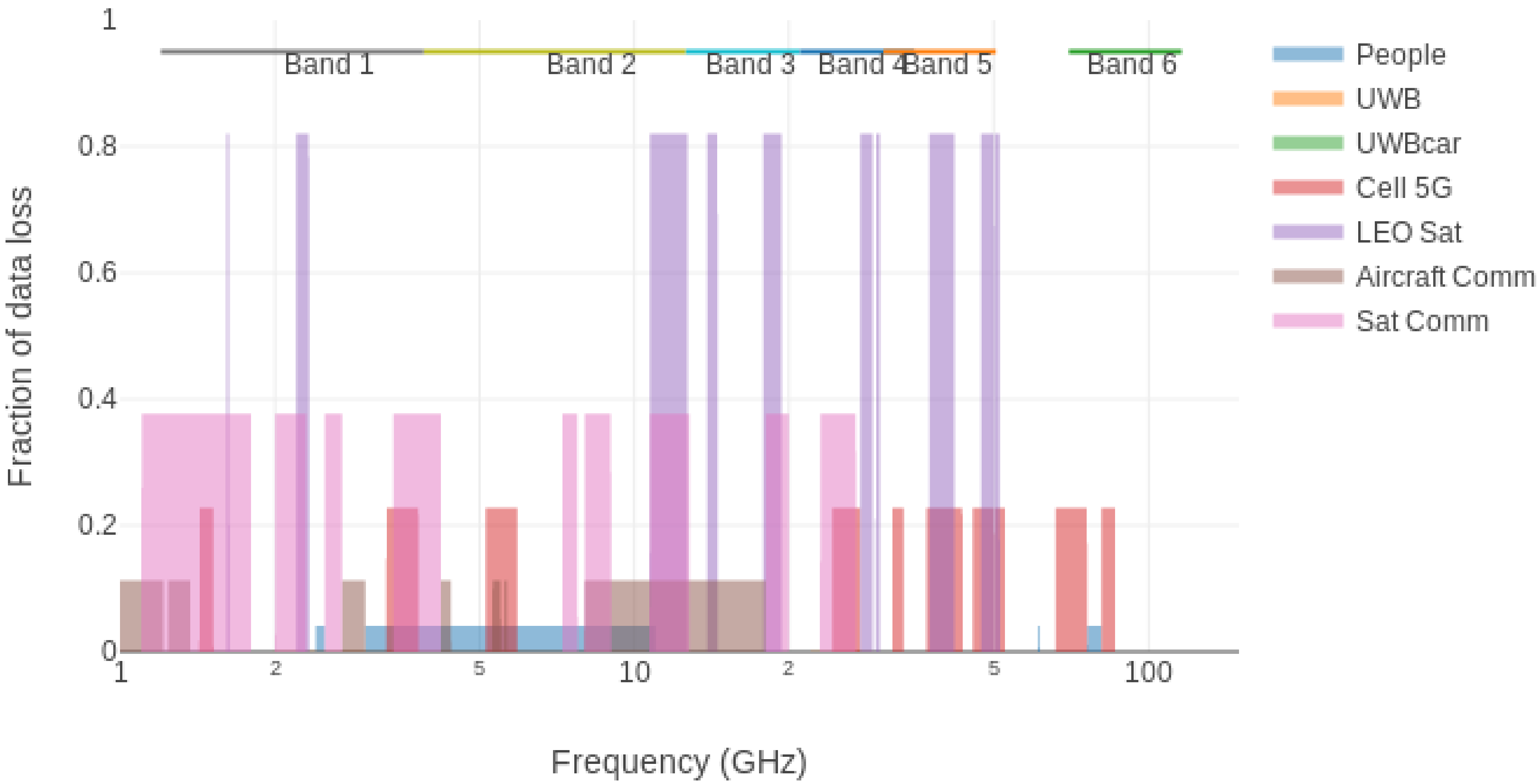


Assumptions : Multiple RFI types with different footprints in frequency, time, and antennas.
Entire allocated band is filled at once (i.e. no usable gaps), no spillover/saturation

Calculations : Fraction of affected baselines, effects of RFI decorrelation and uncorrelated RFI
RFI filling fraction (signal duty-cycle vs data resolution), overlapping vs disjoint RFI

RFI mitigation : Only post-processing flagging

Estimated data loss – RFI mitigation at the antenna

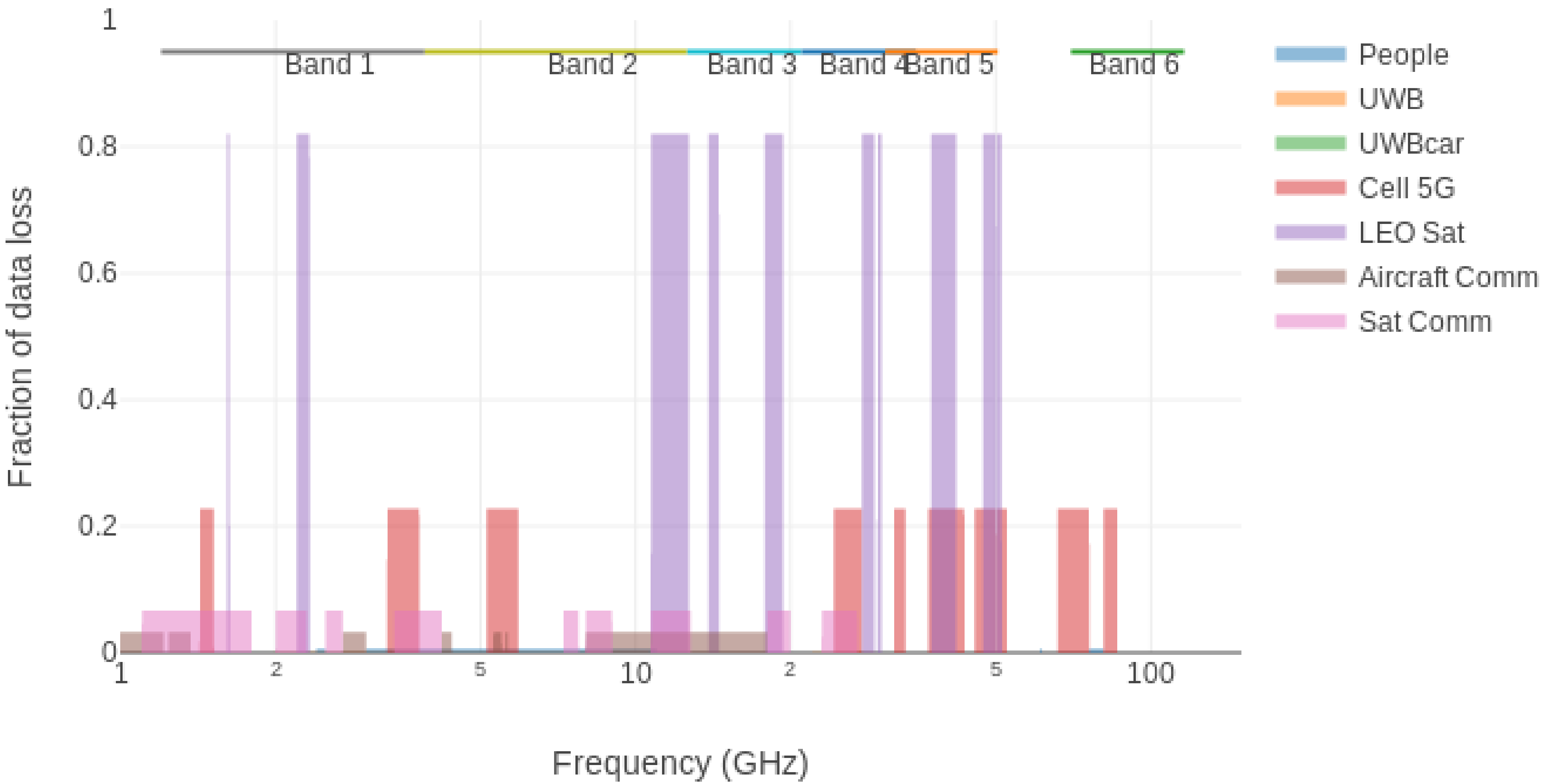


Impulsive, local broadband RFI is removed.

Low impact overall, but useful because of the UWB nature of sparky RFI.

All longer duration RFI persists

Estimated data loss – In-correlator RFI flagging

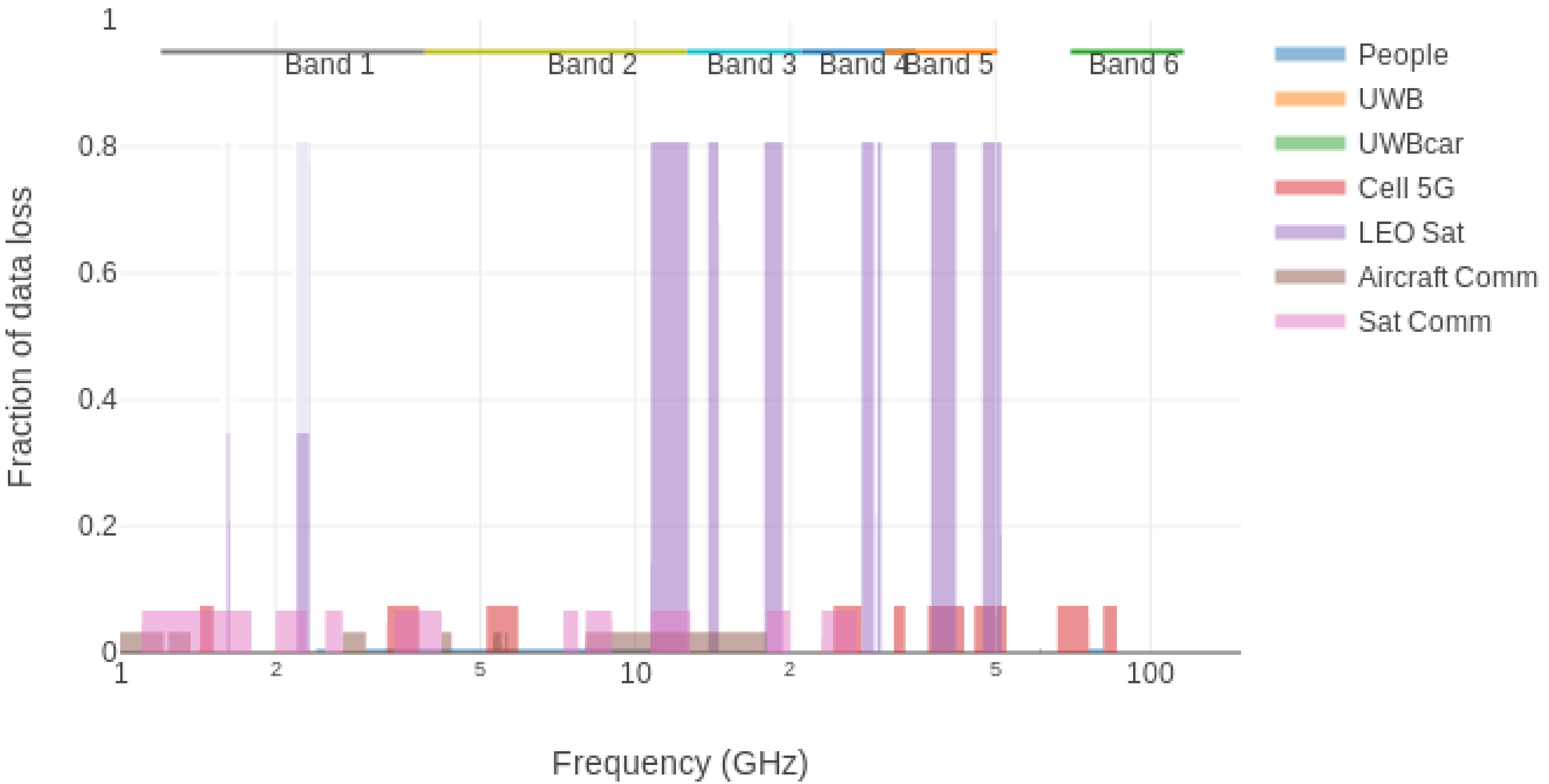


Takes advantage of duty-cycle gaps at the micro-sec to milli-sec timescale

Problem/Question : Do we really have usable gaps ?

Continuous RFI persists : Cell 5G and Satellite Data

Estimated data loss – RFI modeling and subtraction



Models and subtracts continuous RFI signals

Problem : Experiments so far have **not** been very successful

Geostationary/Local RFI is easier. LEO satellite bands may be lost (too many).

Compute Cost

Data rate x Number of operations per datum

For one 100 MHz sub-band,

Data Processing Stage	Time Resolution	Channel resolution	Data Rate (nvis/sec/band)	Number of operations per second (/band)
Baseline based flagging (autoflag + avg)	5 micro sec	100 kHz	6.8e+12 for 263 antennas	1.3e+14 serial (4e+9 for each of 3.4e+4 baselines)
Modeling and subtraction (mod/sub + avg)	1 milli sec	20 kHz	3.1e+10 for 113 core antennas	6.3e+12 serial (1.2e+6 for each of 5e+6 timesteps/chans)
Post-processing flagging (avg-only)	1s	1 MHz	3.4e+6 for 263 antennas	6.8e+7 serial (2e+3 for each of 3.4e+4 baselines)

Caution : Very approximate ! Read only for relative order of magnitudes....

Assumes a relative compute load of 1 : 20 : 200 between
Averaging only , autoflag+averaging, modeling/subtraction+averaging.

How can regulation help ?

(1) LEO satellites : An avoidance zone (footprint) above the telescope

– Main Goal : To avoid saturating entire receiver bands.

=> Data loss is confined to LEO bands only.

(2) 5G Cell Towers :

– No new 5G towers near the ngVLA array core.

- Data loss will be similar to that from LEO satellites (at diff freqs) if cell 5G is active near the core.

– Band-selection for cell 5G towers near ngVLA-spiral antennas.

(3) Other (hard to regulate, but what most of our solutions depend on) :

– The presence of RFI gaps in time and frequency

(4) Protected Radio Astronomy bands :

– Don’t lose them

Summary

Status quo : ~ 30% data loss (on average). 100% in LEO-sat bands.
Observing time nearly doubles (from ideal) in order to compensate
No additional development/operating cost
RFI decorrelation does not help much for 10^4 image dyn-range.

High time-resolution outlier detection :

< 10% data loss in most bands (except cell 5G and LEO-sat)
No significant increase in required observing time (from ideal)
Significant additional development/operating cost

Regulation : Likely required for LEO-sat bands and 5G cell tower location where modeling and subtraction algorithms may work only for simple situations.

This entire analysis is based on many unverified assumptions

– Does the RFI have gaps at high time-resolution ?
– How many interferers can be modeled and subtracted together ?
– How much does decorrelation help/hurt ?
– How viable is the idea of an integrated smart database ?

=> Construct prototypes + borrow from experiments at other observatories.

Experiments and Prototypes

- Pre-correlation RFI detection and blanking / filtering
  - What kind of RFI can we detect ?
  - Replace / Discard / Flag

- Understanding the high-time resolution RFI environment
  – Are there usable gaps in time/freq ?
  – Will current-gen autoflag algorithms suffice ?

- Real-time Subspace projection, Cal-Im, DD-cal-peel
  - Do they work on satellite RFI ? Stationary Cell 5G towers ?
  - Effect of RFI attenuation due to signal decorrelation
  - Are these viable only within the ngVLA core ?

- Scheduling around satellite orbits
  - Possible ? (yes, others have tried it...)
  - What scheduling block size is optimal ?

- RFI monitoring and database generation/use
  - Structure ? What metadata ? How to use the information ?
  - Efficacy ?