CGMS-53-WGI-WP-08

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CGMS Agency Best Practices for RFI Detection, Monitoring, and Mapping for Remote Passive Sensors

WG-I, TGRFI, Section 7.2

For review by CGMS-53

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1. INTRODUCTION

This document presents the CGMS agency best practices (BP) for RFI Detection, Monitoring, and Mapping.

The following "best practice" includes a focus on passive band Radio Frequency Interference (RFI) due to the aggregation of multiple sources of RFI, such as from 5G, where the level of RFI increases over time from a negligible to an insidious and finally to an obvious level of RFI.[1]

International radio regulations contain frequency ranges where radio frequency transmissions are not allowed, although it's possible that excessive anthropogenic energy may be present regardless, such as 5G mentioned earlier. Adjacent frequency band services often have regulatory limits regarding the level of out-of-band emissions that are allowed from those services that may fall into a nearby passive band. As current and future telecommunication services, satellite and broadband-aviation uplinks in millimeter wave bands are implemented, there are potential interference risks to passive sensors, to include operational microwave sensors used by Earth observation satellite systems. This interference could degrade the data used by Numerical Weather Prediction (NWP) Models and other applications, with resulting accuracy degradation. It is desired that members of the Coordination Group of Meteorological Satellites (CGMS) formulate a comprehensive long-term solution through best practices to efficiently and adequately handle radio frequency interference as public demand, new technology system needs, and passive instrument technologies continue to evolve.

Note: Generally, one must differentiate between different types of RFI, such as the typical RFI in SMOS or SMAP data, where often a single source of interference causes obvious RFI (e.g. a powerful radar), and 5G-like systems, where multiple interfering sources in each measurement area aggregate towards RFI.

[1] *SMOS/SMAP-type RFI requires a different approach towards resolving RFI, i.e. chasing the individual interfering source and handling of the individual case with the authority in which the interferer is located.*

Naturally occurring emissions are generally very weak compared to anthropogenic emissions originating from other radio services and it is essential that anthropogenic emissions are identified and kept from adversely contaminating collected Earth observation data.

Commercial RF spectrum advances within and near remote passive sensing frequencies have been identified as posing a significant risk to passive sensing data, due to the following concerns:

- Contamination of passive measurements is a possibility because of adjacent band use.
- It is uncertain precisely as to how interference will be manifested and to what extent.
- It is also unclear how to best minimize the impact of potential interference, and how effectively CGMS members can reduce its impact to the overall global measurements.

Currently only a small number of passive bands have the potential to be affected by planned commercial RF spectrum use. However, there is a very good potential for additional bands to be identified in the future for broadband wireless services and other RF uses as technologies continue to develop and be deployed.

Best Practice Concepts:

2. CHAPTER 1 - FREQUENCY SELECTION

(close coordination between scientists and frequency managers)

Who: project manager, in consultation with frequency managers and scientists

When: before or during Phase 0 (mission definition)

- Trade-off between scientific needs and regulatory/usage situation for the candidate bands. An unfavourable regulatory status (e.g., a weak protection or missing allocation) cannot be easily changed/improved, and it would require a long (at least 5 years) process through a World Radiocommunications Conference (WRC).
- Bandwidth staying strictly within the allocated frequency bands, with consideration of a bit of margin towards the edge of the allocated band to benefit from a bit of roll-off from the unwanted emissions of active services into the measurement bandwidth of the sensor (the margin can also be asymmetrical, depending on the risk of RFI on both edges).
- Trade-off at the level of instrument sensitivity to increase robustness against RFI.
- End-to-end rejection levels at the edges of the allocation need to be sufficiently low.

3. CHAPTER 2 - SETTING OF THEORETICAL PROTECTION REQUIREMENT AND OPERATIONAL REQUIREMENT

Who: frequency managers

When: continuous effort, to keep updated ITU-R Recommendations on protection criteria and sensor characteristics

- The protection requirement is translated from the Noise-Equivalent Delta Temperature (NEDT) to a limit at RF level for a determined percentage of time or area in the footprint size of the sensor.
    - To be able to determine regulatory conditions for services that operate in or adjacent to frequency bands allocated to passive sensors, a protection criterion for spaceborne passive sensors in form of a power density level is established in ITU-R Recommendation RS.2017.
- The protection level/limit for a potential RFI source is simulated for a given deployment scenario of the interferer based on the sensor characteristics and protection criteria available in the ITU-R:
    - Example 5G at 26 GHz: The deployment scenario of 5G, together with the sensor protection criteria, determined the maximum aggregated power level tolerable by the sensor (in Europe the final limit has entered into force 1 Jan 2024; globally if will be 1 Sep 2027). This deployment of 5G can be translated into a deployment density of X base stations per km² in a footprint of the sensor.
- For the assessment of what would or could be the impact of RFI on real measured data, the excess of protection criteria (RF noise floor increase) due to RFI can be backwards translated into a noise temperature increase measured by the instrument on top of the naturally occurring thermal radiation (Gaussian noise).
- Still the most powerful/important mechanism to mitigate RFI is to prevent RFI before it starts at the point where the frequencies of potential future RFI sources are determined, and regulatory conditions are established at national, regional, and international (ITU) level. In this context, one important vehicle to achieve this is the establishment of relevant provisions in the Radio Regulations by decisions of a World Radiocommunication Conference (WRC), e.g. out of band emission limits in Resolution 750 of the Radio Regulations.

4. CHAPTER 3A - DETECTION MECHANISMS FOR KNOWN AND UNKNOWN RFI

Who: project manager, in consultation with frequency managers and engineers

When: initial definition in phase A/B1 (feasibility/preliminary design)

- To identify non or quasi gaussian noise from unknown sources will likely require many algorithms which in turn result in the need of greater processing capabilities/capacities.
- Known sources will only require specific, different, algorithms.
- (Non-exhaustive) list of algorithms that could be required and potentially combined to identify known and unknown sources of RFI:
    - Anomalous amplitude
    - Spectral / Frequency Division (sub-banding)
    - Temporal / Time Division (sub-sampling of the pixel to identify powerful bursts of RFI)
    - Statistical: Kurtosis (measurement of higher order noise statistics that are not Gaussian)
    - Spectral Kurtosis (variation of Kurtosis in time domain or frequency domain)
    - Spatial (adjacent pixel comparisons)
    - Polarimetric: Use of Stokes parameters (dual polarisation on sensors required)

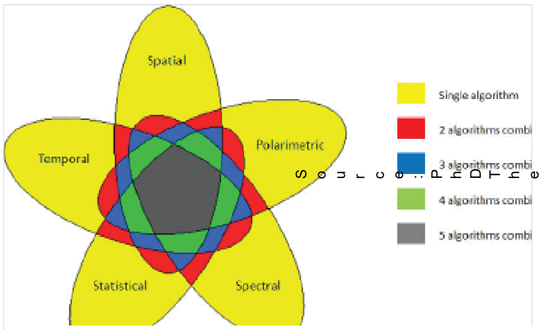


Figure – Interaction of multiple algorithms may be needed to identify unknown sources.

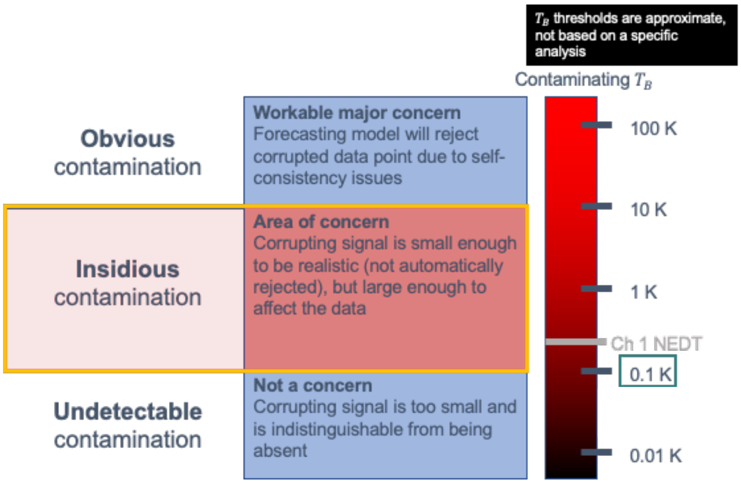
    - Comparison against radiative transfer model/expected values.
- Detection Mechanisms can be applied in various ways:
    - **Spectral** algorithms divide up the signal in smaller frequency "bins".
        - This approach makes good use of a digital back end.
    - **Temporal** algorithms divide up the signal in snapshots of time.
        - This kind of algorithm is more suited to detecting a signal that changes over time like a radar beam consisting of pulses of energy.
        - This approach can be best used to identify and map short radar-like pulses.
    - **Statistical** compares the natural, uniform distribution of the desired signal characteristics – one created by nature, with the non-uniform distribution that would be created by an anthropogenic signal.
        - The technical term for this is kurtosis.
        - This approach is typically combined with other algorithms for improving tests for detecting anthropogenic emissions.
    - **Spatial** would compare each pixel in an image, looking for dramatic changes in brightness intensity.
        - This approach would best support mapping the areas of concern.
    - **Polarimetric** utilizes the geometric orientation of radio signals to differentiate between natural and anthropogenic.
        - This approach requires that the sensor have dual polarization capability.
    - **Machine learning** techniques can be used to classify data samples as “RFI-free” or “RFI-contaminated”.
        - These techniques require a well-defined set of labelled data to train the neural network coefficients
        - These techniques could also be used to categorize the type of RFI signal, e.g. to distinguish RFI coming from communication links, radars, etc., which may be useful in the context of RFI reporting and identification on the ground.

5. CHAPTER 3B - RFI DETECTION THROUGH SENSOR TECHNOLOGY

Who: project manager, in consultation with frequency managers and engineers

When: initial definition in phase A/B1 (feasibility/preliminary design)

- Monitor/mapping of RFI from existing sensors is somewhat limited.
- Methodologies for flagging potentially corrupted data due to RFI, already at instrument level
    - System/technology embedded into the sensor, looking for non-gaussian elements of the signals received by the sensor.
        - Front-end radiometer.
        - Back-end processor (spectral algorithms).
            - Example: MWI on Metop-SG B satellites:
                - MWI instrument implements an RFI detection and mitigation module for the channels at MWI-1 (18.7 GHz).
                - By means of Kurtosis algorithms it will be possible to differentiate non-Gaussian noise (RFI) from Gaussian noise (natural emission).
                - Some parameters of the Kurtosis algorithms can be changed by on ground telecommand.
        - Dual polarisation.



        - In-orbit technology for land surface RFI detection and mapping.
- Sensor calibration to improve robustness from RFI.
    - Example: MWRI on FY-3:
        - Cold calibration target error correction and RFI filtering significantly improved the stability of MWRI's 4 channels.
- Filtering outside of the measurement bandwidth to minimise RFI.
- RFI detection and mitigation techniques (other than identified above)
    - Specific module to be embarked on the satellite (e.g. was under discussion for FY-3, but not yet realised)
- On board selection on which data to downlink (when some RFI detection capability is available on board) – trade-off between data rate and details about the RFI environment.

6. CHAPTER 4 - RFI DETECTION THROUGH DEDICATED INSTRUMENTS OR SATELLITES/CONSTELLATIONS

Who: personnel with the ability to start new developments/studies

When: continuous effort

- Globally standardised satellite-based monitoring facilities.
    - Constellation of small satellites or drones to map the RF environment by area/time.
- Dedicated sensor for a specific RFI source (e.g. 5G RFI identification sensor).
    - In some bands, RF monitoring is commercially available.
    - This may provide an opportunity for making "commercial" buys of RFI information to facilitate RFI mapping and related RFI data completer and more current.
- Preliminary studies ongoing to address this possible detection approach and its multiple challenges, to cover various and larger RF bands and geographical areas.

7. CHAPTER 5 - MONITORING/MAPPING OF THE DEPLOYMENT DENSITY OF THE POTENTIAL SOURCE OF RFI

Who: personnel with the ability to start new developments/studies

When: Phase E (satellite operations)

- Energy is a significant aspect of RFI and is a factor in all RFI occurrences. This issue of energy characteristics relating to the RFI determines the approach towards monitoring and mapping of the RFI.
- Monitoring and mapping are three dimensional, i.e. in time, geography, and energy.
    - Mapping of a globally appearing interference source requires monitoring mechanisms that could support global mapping, for example satellite-based monitoring facilities.

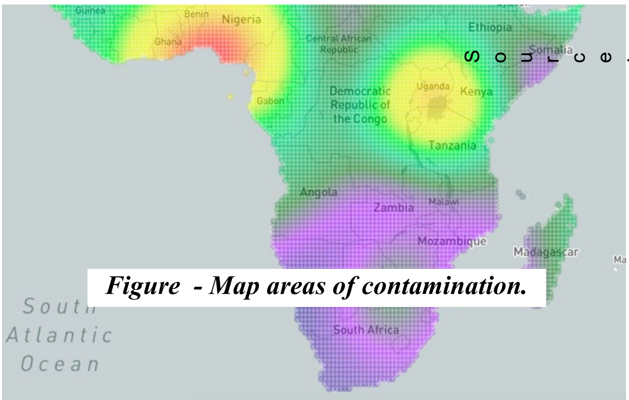


Figure - Map areas of contamination.

- Global mapping also raises the question of possible standardisation of the monitoring facilities?
  - This would require building up monitoring records on measurements for situations and frequencies to which several already operational instruments have reference data which can be later consulted and compared once the deployment of the RFI sources increases, allowing for long term RFI trend observations.
  - Use of common RFI databases enabling satellite groups to collectively maintain current maps of RFI sources or spectral densities of anthropogenic RF emissions of concern to remote sensors.
- The deployment density can then be monitored, and the progressing deployment can be compared over time with the instrument data acquired. This comparison could be done at the level of "European Centre for Medium-Range Weather Forecasts" (ECMWF), the "Center for Satellite Applications and Research" (STAR), or equivalent.
  - Procedures for reporting an RFI assessment need to be established and globally used in the meteorological and climatological communities.
- Once the deployment density reaches the theoretically determined critical density in each area, the monitoring of the acquired data can be intensified, consequentially.
  - Determine methodologies/algorithms for flagging potentially corrupted data due to RFI.
    - RFI: Based on changes in the BIAS or random errors.
    - Comparison of brightness temperatures.
    - What would be the difference in Kelvin that is detectable?
    - Different Algorithms for known sources; many algorithms necessary for unknown sources, until known.
  - Forecast Sensitivity - Observation Impact (FSOI) statistics may be a way to compare observational data with the theoretical simulations and then compared to maps of RFI once established.
  - Monitoring based on comparison with other observation frequency channels, recording the evolution of the BIAS (or error) over time.
  - Trend observations over a longer period over more than one instrument.
  - Monitoring results would be more conclusive when analysing over a longer period (e.g. 10 years) at specific areas (e.g. densely populated, hot spots, coastal areas, etc.)
    - How does the ECMWF 10-year-strategy (all sky all surface) take this into account?

8. SUMMARY

Best practice	Who is responsible	When it should happen
Select frequencies, considering the level of regulatory protection	Project manager, supported by frequency managers & scientists	Phase 0
Set / update theoretical protection requirements and establishment of regulatory limits to be protected from RFI as globally as possible	Frequency managers [supported by scientists]	Continuous work
Define hardware and software for RFI detection	Project manager, supported by frequency managers & engineers	Phase A/B1
Map, monitor and report RFI	Agency personnel, supported by frequency managers	Phase E
Develop payloads/missions dedicated to RFI detection	Agency personnel, supported by frequency managers	Continuous work

9. CONCLUSION

As mass market RF intensive applications approach, reach, or even exceed the tolerable numbers of deployment for those applications, sophisticated monitoring processes and systems will be needed for determining and monitoring where RFI occurs:

- Spatial and spectral characterization of RFI requires the selection of a threshold level above which data are flagged as contaminated by RFI.
  - This threshold level must be established between a level of contamination in the models and products that would still render usable data.
  - This threshold level would have to be determined by the national and regional forecast centers, such as NCEP (in the US) and ECMWF (in Europe).
- The protection criteria in ITU-R Recommendation RS.2017, is a reference and suggested possible starting point to determine an absolute level of acceptable contamination.
- Consideration must be given to the aggregate level of RFI that may originate from one service with many transmissions at the same time and in the same area (e.g. 5G) or from several different radio services. Accordingly, each regulatory provision applicable for adjacent active services that may limit the contribution to contamination of a passive band should be envisaged, most effectively by means of provisions in the ITU-R Regulations established at a WRC.
- As the data are acquired by a global network of sensors on meteorological satellites, exchanged and fed into global forecast models, also the threshold selection should ideally be decided collectively by the international partners for global consistency.
  - Requires establishment of RFI properties to catalogue for characterization.

- Any RF source characterization, as a minimum, should include energy, spatial and temporal descriptions. The characterization of a globally appearing interference source should consider monitoring mechanisms that could support global mapping, for example satellite-based monitoring facilities.
- Universal characterization also raises the question of possible standardization of the monitoring facilities which should also be considered.
- Standards relevant to remote RF passive sensors do not currently exist for measuring, evaluating, and mitigating RFI affecting spaceborne Earth observation satellites.
- Remote passive sensor design, development and implementation should consider RFI detection and mitigation as an aspect of their system design.

It can be assumed that the global level of RFI is gradually increasing over time with the aggregation of single low level interfering signals up to a point when RFI becomes obvious. Thus, RFI can be expected to move from undetectable levels, then to levels of "insidious" data corruption, and then to levels of blatant data contamination, such that the data can only be discarded. (See figure 2.) Insidious data corruption means there could be RFI (data corruption) induced into the measurements unnoticed for a significant period as the measurements are erroneously taken as correct measurements without any interference component.

Therefore, monitoring of the development of mass market RF intensive applications is a factor for consideration in the characterization process and as part of a best practice. This also requires building up monitoring records on measurements of already operational instruments to have reference data that can be later consulted and compared once the deployment of these RF intensive applications sufficiently increases. This allows for long term RFI trend observations.