COMMERCE SPECTRUM MANAGEMENT ADVISORY COMMITTEE (CSMAC)

Report of Subcommittee on Electromagnetic Compatibility Improvements

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FINAL REPORT

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I. OVERVIEW OF NTIA TASK.

The National Telecommunications and Information Administration (NTIA) provided the following background and questions to the Electromagnetic Compatibility Improvements (ECI) subcommittee.

Background. As the spectral environment continues to become more congested and spectrum sharing becomes more common, the potential for adjacent channel interference scenarios remains a limiting factor in expanding access to spectrum. Government radar bands increasingly are being identified for sharing with commercial or other government systems.

Question: To increase the efficient use of the spectrum resource:

- How can radar and other systems better co-exist in co-channel and non-co-channel relationships?
- How should statistical risk-based analysis techniques in spectrum compatibility modeling be used to characterize operational impacts to federal systems?
- What improvements in propagation modeling would increase the accuracy?
- What role should NTIA play in ensuring the independent and timely analysis of these potential interference scenarios?
- Other improvements suggested by CSMAC.

In response to follow up questions from the ECI subcommittee to NTIA, NTIA clarified that it would like the focus to be on how best to analyze the compatibility between commercial wireless systems and federal aeronautical radar systems operating in the 5 to 16 GHz frequency range. NTIA is seeking input on potential methodologies and types of inputs required for an appropriate statistical analysis, rather than having the subcommittee conduct any analysis. The subcommittee also agreed to provide recommendations concerning enforcement issues as part of its report to NTIA. The subcommittee worked to develop an overview of the current NTIA/federal agency/Federal Communications Commission (FCC) process for interference analyses and provide recommendations on how to make this process as independent and timely as possible. In accordance with the focus indicated by NTIA, this report provides recommendations to improve electromagnetic coexistence compatibility studies between wireless communications and aeronautical radars in the 5-16 GHz frequency range without making any determination regarding the applicability to other bands and services.

II. RADAR DISCUSSION.

The attached Appendix III provides a description of certain federal aeronautical radar systems operating in the 5-16 GHz frequency range by band segment. Compiled aeronautical radar information was derived from federal government publicly available sources only. The sources for the information provided below are the following:

- The Federal Spectrum Compendium https://ntia.gov/page/federal-government-spectrum-use-reports-225-mhz-7125-ghz
- Federal Radar Spectrum Requirements, NTIA Special Publication 00-40, May 2000, https://www.ntia.doc.gov/files/ntia/publications/ntia00-40.pdf

- Federal Spectrum Use Summary 30 MHz – 3000 GHz, NTIA OSM, June 21, 2010 https://ntia.doc.gov/files/ntia/Spectrum_Use_Summary_Master-06212010.pdf
- Spectrum Management Regulations and Procedures Manual, FAA, 6050.32B, November 17, 2005 (Effective 6/11/2019), https://www.faa.gov/documentLibrary/media/Order/6050.32B_with_Changes_1_2_3.pdf

In addition to this background information, the subcommittee interviewed subject matter experts from the National Aeronautics and Space Administration (NASA), Garmin, the Federal Aviation Administration (FAA), and Collins Aerospace.

NASA. NASA operates several categories of radars within the 5-16 GHz frequency range including:

- Launch Range Operational Support Radars (including airborne radar transponders on launch vehicles)
- Terrestrial Earth Exploration Science Radars
- Airspace Surveillance Radars for Laser Safety
- Solar System Debris Tracking Radar
- Maritime Navigation Radars
- Speed Control Radars
- Aeronautical Radars
- Earth Exploration-Satellite (Active) Sensors

NASA aeronautical radars in the 5-16 GHz frequency range can be further divided into two categories: (1) typical aircraft weather radars (FCC Part 87 systems) and (2) airborne Earth exploration science radars. The first category of NASA aeronautical radars, typical aircraft weather radars, are commercially available radars operating in the 9300-9500 MHz band that are used by aircraft to detect weather phenomena as they relate to aircraft flight operations.

The second category of NASA aeronautical radars are airborne Earth exploration science radars used to collect a variety of weather phenomena and science data. These radars include:

- NASA 2nd Generation Airborne Precipitation Radar (APR-2): Dual-frequency, dual-polarization, Doppler radar used to construct a 3-dimensional (3D) representation of precipitation below the aircraft including classification and velocity of precipitation particles (with cross-track scanning); 13405 MHz [NASA123023] and 35605 MHz [NASA123022].
- NASA 3rd Generation Airborne Precipitation Radar (APR-3) (identical to the APR-2 with the addition of W-band sensor): Tri-frequency, dual-polarization, Doppler radar used to construct a 3D representation of precipitation below the aircraft including classification and velocity of precipitation particles (with cross-track scanning); 13405 MHz [NASA123023], 35605 MHz [NASA123022], and 94920 MHz [NASA983026].

- NASA Snow Water Equivalent Synthetic Aperture Radar and Radiometer (SWESARR): Tri-band synthetic aperture radar (SAR) and tri-band radiometer used to measure land surface snow depth and remotely determine the resulting water content within the snowpack (Snow Water Equivalent (SWE)); active sensors: 9650 MHz [NASA165504], 13600 MHz [NASA215568], and 17250 MHz [NASA215564]; passive sensors: 10600-10700 MHz [NASA215565], 18600-18800 MHz [NASA215566], and 36000-37000 MHz [NASA215567].
- NASA Hi Altitude Imaging Wind and Rain Airborne Profile (HIWRAP) Radar: Dual-frequency, dual-beam, Doppler radar system used to image winds through backscattering from clouds and precipitation enabling it to measure the tropospheric winds above heavy rain at high levels; 13400 MHz [NASA125540], 13750 MHz [NASA125541], 33400 MHz [NASA125542], 35500 MHz [NASA125543].
- NASA ER-2 X-band Doppler Radar (EXRAD): Dual-beam Doppler radar used to construct a 3D representation of precipitation and winds below the aircraft to study various weather phenomena such as convective precipitation and tropical cyclones, as well as providing data to improve and validate satellite precipitation estimates (NASA Global Precipitation Measurement (GPM) Mission); 9600 MHz [NASA125538], 9620 MHz [NASA125539].
- New airborne scientific radar under development by BAE Systems Information and Electronic Systems Integration Inc. (BAE Systems) to demonstrate scientific capabilities to NASA and NOAA: Radar designed to operate from a Gulfstream V aircraft to collect data on storm events as the aircraft with the radar system flies in the immediate vicinity of the storm (primarily above and adjacent); 9300-9500 MHz [FCC Experimental License 0099-EX-ST-2023].

In addition to the airborne Earth exploration science radars, NASA also operates spaceborne sensors in the Earth Exploration-Satellite (active) Service (EESS). This currently includes the NASA Global Precipitation Measurement (GPM) Mission, which is the first space-borne dual-frequency precipitation radar and multi-channel GPM microwave imager (GMI) used to provide 3D measurements of precipitation structure and characteristics; active sensors: 13597 MHz [NASA135529], 13603 MHz [NASA085503], 35547 MHz [NASA085505], 35553 MHz [NASA085506]; passive sensors: 10600-10700 MHz [NASA135522], 18600-18800 MHz [NASA135523], 23600-24000 MHz [NASA135524], 36000-37000 MHz [NASA135525], 86000-92000 MHz [NASA135526], 163.5-167.5 GHz [NASA135527], 175.31-177.31 GHz [NASA215528], 179.31-181.31 GHz [NASA215529], 182.31-184.31 GHz [NASA135528], 185.31-187.31 GHz [NASA215530], 189.31-191.31 GHz [NASA215531].

Garmin. Garmin indicated that aviation and marine radars are manufactured by Garmin that operate within the 9.3-9.5 GHz band. The aviation radars are for onboard weather detection by aircraft, constantly scanning for weather during all phases of flight normally (but a pilot can turn it off/auto control if needed). These systems are part of an aircraft minimum equipment list (MEL) and therefore need to be operational before flight. They can create a radiofrequency (RF) hazard at the airport gate, so they are often switched off when the aircraft is parked.

Aircraft weather radars operate on a semi-swept scanning process, though weather targets do not require high resolution since weather targets are typically miles across. Systems maximize sensitivity for extra margin as the system is looking for very weak returns, with a 1 dB loss of sensitivity equivalent to raising the noise floor (approximately -130 dBm) by 1 dB. Their most challenging environment is near the airport as air debris (insects and dust detection) cause performance degradation.

Both vertical and horizontal scans are normally made, with newer models having 3D volumetric scan to remove ground clutter. The scans can be standalone or integrated into display for pilots. The minimum operational performance standard (MOPS) specifies a main beam pattern of +/- 15º vertical +/- 30º horizontal from the front of the aircraft. Newer solid-state models are frequency agile to avoid mutual interference from other weather radars, and some radars can hop between frequencies to avoid noise or interference at specific frequencies. The radars are not coordinated with other radars, but the band is large enough to support many simultaneous users.

The duty cycle is normally 10% for solid state and 1% for magnetron systems (varies with performance requirements). Standards for receiver selectivity have not been a major focus in the 9 GHz band as the band has not been the subject of significant allocation changes. Equipment Location – Certification Information Database (EL-CID) formatted files filled out with parameters for federal agencies users may have receiver characteristics as part of the system certification process.

FAA. The FAA does not generally perform risk-based spectrum analyses when modeling operational impact to its system but instead considers risk when developing system requirements. The agency does apply some risk-based analysis to propagation modeling to consider variability in impacts due to clutter and atmospheric effects and may apply some risk-based analysis to wide-area multilateration where it is applicable. The FAA indicated that it has a detailed process for choosing the spectrum bands that are technically suitable for its radar operations and how it develops protection requirements.

Collins Aerospace. Collins Aerospace currently manufactures five different airborne weather radar systems, all are solid-state transmitters operating in parts of the 9.3-9.5 GHz band in a pulsed mode. The radars detect a combination of range, reflectivity, and velocity of weather effects that are designed to alert pilots to presence of weather to 320 nautical miles, turbulence to 40 nautical miles, and hazardous low altitude microbursts (predictive windshear) to 5 nautical miles. These radars are certified using FAA TSO-C63(x) and RTCA DO-220 as Minimum Operating Performance Standard (MOPS) and are used both by industry and federal agencies (DOD radars have military nomenclature but operate with the same frequencies, mission, and characteristics as their civilian counterparts). Several agencies (such as NASA) also use the radars for research purposes where the hardware is the same, but they apply different processing to the output.

Radar coexistence around and in a congested airport environment needs to solve the problems of both co-illumination (seeing multiple other radar returns from the same object), and direct illumination (direct coupling of transmissions from another weather radar if aircraft are pointing at each other). Balancing these two requirements can be challenging for both ground and airborne operation of the weather radar, especially needing to account for older radars on some aircraft that can emit 20-30 kW of power while still being sensitive enough to integrate weaker reflected returns from dust, moisture, and other airborne debris. The most challenging problem is when the noise floor is raised by co-channel and adjacent channel interferers, especially in areas around airports where radars with predictive windshear detection modes are active. Predictive windshear detection is an example of a radar detection mode with signal detection requirements very close to the noise floor of the radar systems. The mode uses coherent and non-coherent integration of pulses to extract microburst Doppler characteristics from ground clutter.

Further analysis is needed as operational remedies are unlikely and technical changes that may be feasible each have their own tradeoffs to consider. For example: increasing the transmitted power (though this could degrade other aircraft nearby), generating more waveforms/pulses so the signal can be integrated over a larger time/frequency domain (but are then more susceptible to other high-power transmissions), and improving interference rejection (limited by these other transmissions being in the receiver front end passband). Predictive windshear operation is dictated by FAA regulations which are, in turn, based on analysis of sensor operation and requirements needed to maintain safe aircraft operation.

Interference modeling can be complex in a 3D environment with directive antennas and the noise floor sensitivity of the systems. Previous manufacturer assessments have been deterministic given the assurance needed to operate, though these have inbuilt statistical requirements that are unique to each manufacturer on areas such as false alarm and alerts rates. These parameters are proprietary and any assessment needing to utilize them would require each weather radar manufacturer to be directly involved with a method to ensure some proprietary data is kept non-public and not visible to other manufacturers. Any analysis would likely be incomplete without manufacturer involvement.

III. COMMERCIAL WIRELESS COEXISTENCE MODELING.

As part of any coexistence analyses, NTIA should seek to model commercial wireless systems to reflect how they would be deployed in the US, based on both the actual capabilities and requirements of 3GPP or other standards' required capabilities. When modeling commercial use of the spectrum, NTIA should consider the limit values for transmitter powers and out-of-band emissions (OOBE) specified in FCC rules unless commercial parties are able to provide more relevant values that are then agreed by all relevant parties to be used for modeling.[1] Commercial wireless network operations are generally dictated not only by the power and generic emission limits found in the FCC's rules[2] but also by standards bodies such as 3GPP, and individual operators' own network deployment parameters, which could vary by location and time. In particular, 3GPP TS 38.101 and TS 38.104 provide the specifications for minimum RF performance requirements of transmitters and receivers operating in accordance with the 5G NR standard for User Equipment (UE) and Base Stations (BS), respectively. Should coexistence analysis between 5G NR commercial networks and federal radars operating in the 5-16 GHz frequency range be undertaken, commercial wireless providers could develop and provide

[1] For example, when NTIA studied the 3.45-3.55 GHz band, it utilized three sets of EIRP values for deployments, with all base station, access point, and user equipment OOBE based upon values from the Commission's existing commercial wireless rules. *See* Edward Drocella *et al*, Technical Feasibility of Sharing Federal Spectrum with Future Commercial Operations in the 3450-3550 MHz Band, NTIA Technical Report 20-546 at 12 (Jan. 2020) (found at: https://www.ntia.gov/report/2020/technical-feasibility-sharing-federal-spectrum-future-commercial-operations-3450-3550).

[2] In addition to generic FCC rules for power and OOBE limits, ITU parameters (for example ITU-R Appendix 3/SM.329) could also be used.

standards-based parameters as a starting point to model their operations. Alternatively, NTIA should note that any modeling process would be an iterative one—as new technical standards, equipment testing, and use cases are developed, there should be a well-defined process coordinated with the FCC for allowing commercial parties to update the technical specifications used in modeling. However, NTIA, the FCC, federal and non-federal users, and radar manufacturers need to take into account that the iteration would be two-way, as the federal and other coexistence stakeholders (including radar manufacturers and non-federal users) will also seek to innovate and improve their capabilities.

Future commercial wireless systems are expected to also rely upon a combination of FCC rules and 3GPP standards. Additional analysis would be necessary to better understand and account for features that are likely to be used in actual wireless deployments, as well as potential mitigation techniques that might be used to limit the interference potential from these systems in a tailored manner. However, depending on network conditions such as BS loading, which could vary significantly with environment and deployment density, the peak powers listed for base and mobile stations could occur in rare instances in some environments such as rural, but could be more prevalent in dense urban areas.

As discussed in detail below, statistical analysis should be utilized to model the operations of commercial wireless systems more accurately and to reach determinations about the likelihood of harmful interference caused or received by these systems. In addition, commercial wireless networks are subject to constant change, optimization, and maintenance by network operators. A cumulative distribution function would be a more accurate model of actual operating powers throughout a market and could be developed and provided to NTIA by industry based on actual market layouts of similar frequency bands and environments that take into consideration the real-world network (including density of cell sites, inter-cell site distances, BS loading, time division duplex (TDD) activity factor, and other network information). Commercial wireless providers would need to provide this type of information as part of the modeling process, either at the start of the process if available, or as those data are developed and can be made available to NTIA. Alternatively, NTIA could itself or through other companies measure mobile network deployments to determine this information. Starting such a process without the relevant data is of questionable value and policy decisions need to be informed by more stable and relevant modeling.

Finally, there are other mitigation techniques that can be utilized in commercial networks to avoid interference that should be part of any coexistence determination. For example, antenna down tilt could be increased depending on the market and network configuration (and the federal radar system protection criteria). More directional antennas could be deployed—mitigating the interference transmitted or received in certain directions. In many terrestrial interference cases, analysis reveals that a sizeable majority of the interference is caused by a very small number of interfering stations. Specific mitigation measures could be tailored to address those top-interfering stations in a much easier and more economical way than blanket application of mitigating measures such as EIRP or PFD limits. Regulatory frameworks premised upon coexistence need to reflect detailed mitigation requirements.

Another important step in determining coexistence is for involved parties to use a mutually agreed methodology in modeling the commercial wireless network. Past experience has shown that lack of an agreed methodology could lead to significant differences in results, which can lead to significant timeline delays to resolve discrepancies. For the case of 4G/5G mobile systems, Recommendation ITU-R M.2101 offers a generic methodology which can be tailored to the coexistence scenario at hand.

In summary, there are several assumptions that should be considered and agreed to between the commercial wireless industry, affected federal agencies, aeronautical radar and other relevant OEMs, and NTIA when developing parameters for coexistence modeling. To best reflect the actual operating environment, it will be vitally important for NTIA to work collaboratively with the commercial wireless industry, radar manufacturers, and other relevant OEMs to reach consensus on modeling methodologies and technical parameters.

IV. COEXISTENCE ANALYSIS.

As industry standards bodies are driven to identify government radar bands for commercial wireless, methodologies for radars and other systems to better co-exist in co-channel and non-co-channel relationships require exploration. When making an allocation or frequency assignment, spectrum managers consider the potential for harmful interference to operations in shared bands or to operations in adjacent bands.[3] Technical spectrum studies (or electromagnetic compatibility studies) are one important tool spectrum managers and users can use to assess the probability of harmful interference.

A risk assessment can be part of technical spectrum study,[4] which is a piece of the risk management framework (RMF)[5] or enterprise risk management (ERM).[6] In this context, a technical spectrum study quantitatively characterizes the uncertainty and variability in estimates of exposure or risk (harmful interference).[7] The study quantifies the relative contribution of these sources (of variability and uncertainty) to the overall variance and range of the output or results.[8]

Traditionally, terrestrial licensed spectrum has been allocated and been assigned using the parameters of frequency and geography, where a specific range of frequencies is dedicated to a particular use or user in a geographic area, and the geographic area impacted is determined by the power of the RF emission transmitted by a system and the direction of transmission. Time variability of radiated power and spectrum occupancy are now becoming important factors as shared use of frequencies is becoming a necessity. Further, systems under consideration are increasing in complexity, and statistical analysis between systems that are candidates for

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[3] "The Federal Government considers that the basic guide to follow in the normal assignment of radio frequencies for transmission purposes is the avoidance of harmful interference and the use of frequencies in a manner which permits and encourages the most beneficial use of the radio frequency spectrum in the national interest." *See* https://ntia.gov/publications/redbook-manual. *See also* "Harmful Interference: Interference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with these regulations*." Id.*

[4] "A risk assessment is a process to identify potential hazards and analyze what could happen if a hazard occurs." *See e.g.*, https://www.ready.gov/risk-assessment.

[5] *See* https://csrc.nist.gov/projects/risk-management/about-rmf; *see also* https://www.osec.doc.gov/opog/privacy/Memorandums/OMB_Circular_A-123.pdf.

[6] *See* https://www.osec.doc.gov/opog/privacy/Memorandums/OMB_Circular_A-123.pdf .

[7] See attached Appendices I and II for a discussion of variability and uncertainty.

[8] Not every assessment requires, or warrants, a quantitative characterization of variability and uncertainty; for example, if the analysis, using conservative point estimates, does not show that harmful interference will occur there is no need for a quantitative characterization.

spectrum coexistence is necessary. Additionally, intermodulation interference could be a significant problem when systems with disparate power levels are attempting to coexist.

A. Potential Methodologies for an Appropriate Statistical Analysis Between Aeronautical Radar and Commercial Wireless Systems in the 5-16 GHz Frequency Range.

When initiating a statistical analysis to examine sharing between radar and commercial wireless systems, NTIA might consider both interference risk-based and performance degradation statistical analysis approaches.

Interference risk-based statistical analyses establish a set of protection thresholds associated with a receiver. These thresholds are system-dependent and can be based on when interference begins to degrade receiver operation (i.e., the onset of interference), when harmful interference begins to occur (i.e., the receiver consistently is unable to perform its function), or other criteria established by the system operator. The analysis method considers the probability that an interference event will occur, typically by focusing on the time-varying nature of possible interference and assesses the signal characteristics against the receiver thresholds. NTIA, in developing a framework for coexistence analysis, should acknowledge that different agencies/commercial industries have very different metrics for defining the risk of interference. When establishing this process, NTIA should ensure that there is no "one size fits all" metric and that each agency/industry should be engaged to develop these interference probabilities that best represent the needs of each party. In the attached Appendices I and II, a contribution discussing risk-based and performance degradation statistical methodologies is provided for background on this issue. This issue has also been studied in detail at the FCC's Technological Advisory Council, including a case study of coexistence using a risk-informed interference assessment.[9] NTIA should translate interference in the radiofrequency realm into risk measures that could be defined as the tolerance for interference that a particular system could manage. Risk measures could be used to model the statistical likelihood of harmful interference and be based on the government-determined tolerance for risk (including degradation and/or disruption) for the spectrum user under study.

Performance degradation statistical analyses focus broadly on overall signal quality at a receiver. This methodology includes the contributions of natural sources of degradation, such as noise, rain, propagation impairments, and other natural phenomena. Signal quality, as measured by maximum allowed degradation to a set of system performance metrics, at the receiver is then assessed in the presence of both natural degradation sources and interference.

When performing statistical analyses to determine the likelihood of interference under a variety of conditions, simulations (usually Monte Carlo simulations) are performed using a model of the environment under consideration. A number of inputs, as described below, are required by the models that are used to predict the signal levels at the receiver. The models themselves are numerous and varied, and aspects of modeling are discussed in a subsequent section of this report. After determining the source(s) of interference, the propagation

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[9] *See* https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting4115/Intro-to-RIA-v100.pdf (discussing Risk Informed Interference Assessment); *see also* https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting121015/MetSat-LTE-v100-TAC-risk-assessment.pdf (case study of risk-informed interference assessment between MetSat and LTE in the 1695-1710 MHz band).

characteristics of the environment, and the resulting signal levels at the receiver, the impact on receiver performance is assessed and a determination of severity of interference is made. To aid in the independent verification of results, the simulation should output various interim data along the interference path. For example, the EIRP for each time sample is useful to plot and quickly compare with expectation. Those preparing analyses could also consider including sensitivity analyses that demonstrate which inputs have the most impact on the relevant output. Data like these adds transparency that leads to certainty that the above models are trustworthy and representative of the actual systems.

In considering interference from a statistical standpoint, it is important to look at the data that have pragmatic importance. For instance, when considering a cumulative distribution function (CDF) of interference produced by a Monte Carlo simulation, the number of samples exceeding the interference threshold are important, but as important is also consideration of the degree each sample is exceeded or potentially how long the exceedance may last, and sensitivity analysis can help to identify which factors have the greatest impact on the results. Such data could possibly point to practical mitigation techniques to remove very small exceedances and help to determine the best approach to maximize coexistence without unnecessarily inhibiting spectrum usage.

B. Types of Inputs Needed for Statistical Analysis.

Statistical analyses between radar and commercial wireless systems in the 5-16 GHz frequency range should consider or, at minimum, gather the following types of inputs for transmitters and receivers. These inputs encompass the characteristics of the transmitters that could cause interference, the physical environment through which the signals travel, and the characteristics of the receivers that could be degraded due to the transmitted signals. In addition, there needs to be an understanding of the operational impacts, not just the technical parameters when conducting a coexistence analysis. Agreement must be reached among all stakeholders about the operational effects associated with coexistence and this should be factored into the statistical analysis process.

The necessary technical inputs account for the different interference mechanisms, both to and from existing federally operated radar systems. For example, adjacent band analysis would need to consider the effects of both fundamental and unwanted emissions to and from federally operated radar systems.

i. Transmitter and environmental inputs.

Transmitter modeling needs to consider both the technical characteristics of the transmitters for both federal and non-federal systems, such as the type of emission, electronics and antennas, and the deployment of the transmitter system, such as the numbers and locations of transmitters. Transmitter signal information depends on the type of transmitter (e.g., base station, mobile network user equipment, radar, etc.) and should include the frequency, EIRP, bandwidth, antenna characteristics, signal types (continuous wave or pulsed) and time-varying characteristics such as duty cycle. These parameters may be characterized as a single value or a distribution of values that may independently or dependently vary as a function of another station. For adjacent band studies, the out-of-band emission performance of the transmitter should also be considered and compared with similar systems to determine whether unwanted emissions could be further reduced.

Transmit antennas for systems such as 5G and modern Wi-Fi standards are becoming increasingly complex due to multiple input/multiple output (MIMO) configurations and adaptive arrays. The transmit antenna pattern should be represented in 3D space, and the antenna pointing behavior, if applicable, should be represented as a distribution that characterizes the orientation (as opposed to a static orientation) and beamwidth, and other time-varying characteristics based on system loading and TDD activity ratios when applicable.

Finally, transmitting stations should be modeled as a system. For example, in a mobile network such as LTE or 5G-NR, the transmitting station behavior, user equipment (UE) uplink power control algorithm, antenna characteristics, and signal information need to be considered for a collection of transmitters in an area. For both base station and UE transmissions, the number of transmitters plus transmitter topology (e.g., locations in a given environment including colocation of transmitters), density (i.e., the distance between transmitters in an area), power (variable in a system depending on time, load, or other factors), antenna pointing, and antenna height are all factors that contribute to a spectrum sharing environment. These factors are critical to model as distributions to account for the many possible variations. Commercial providers would need to provide this level of granular data to NTIA for coexistence modeling, if available. Absent that, NTIA could measure and derive these parameters, or would need to rely upon generic power/OOBE values (as discussed above) and should have an established process to iterate coexistence requirements based on new technical information being provided by the commercial wireless industry.

Transmitting stations need to be considered as a system, for both federal and non-federal transmitters. For both commercial wireless network topology and aeronautical radar use, the transmitting stations' area of operation, behavior, antenna characteristics, and signal information need to be considered for a collection of transmitters in an area. The number of transmitters plus transmitter topology (locations), density (transmitter separation distance in an area), power (which is variable), antenna pointing, duty cycle, and antenna height are all factors that contribute to a spectrum sharing environment.

ii. Receiver inputs.

Similar to transmitter modeling, receiver modeling for federal and non-federal systems needs to take into account both the technical characteristics of the receive system, including effective sensitivity, frequency response, and antennas, plus the deployment (numbers and locations of receivers). Receiver modeling requires additional information to determine the effect of potential interfering signals on overall system performance to assess the effects of degraded receiver performance and thus the severity of the interference. This additional information includes error handling and fallback, associated interference thresholds, and the interference management topology, if any, such as retransmission, signal processing, speed reduction, and interference cancellation.

Receiver performance can have multiple expressions and is meant here to be ability of the receiver to effectively detect the desired signals and reliably perform its intended function. In a communication system, the main parameter used for assessing the impact of an interferer might be signal-to-noise plus interference ratio (SINR), and in a radar system, this parameter might be radar pulse resolution. Once the parameters that identify the level of interference of a received signal are identified, thresholds for assessing the level of interference need to be established for each parameter based on operational and technical requirements.

Receiver bandwidth is an important consideration for both co-channel and adjacent channel analyses, as it is impossible for receivers to be built with perfect "brick wall" filtering. For interference risk-based analyses, the protection criteria(on), including receiver filter characteristics, image response in heterodyne receiver designs, etc., should be input to the simulation. For adjacent band studies, the passband and baseband filter performance specifications should be provided, as well as antenna frequency dependent rejection and receiver sensitivity requirements.

C. Use of Statistical Analysis by Federal Agencies.

Federal agencies have documented the utility of Monte Carlo simulations in contrast to other mathematical models. The subcommittee recommends that NTIA review the references below and determine if any could be applied or adapted to simulations done to model the radiofrequency environment.

1. DoD Cost Estimating Guide: https://www.cape.osd.mil/files/Reports/DoD_CostEstimatingGuidev1.0_Dec2020.pdf
2. Department of Defense Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs: https://acqnotes.com/wp-content/uploads/2017/07/DoD-Risk-Issue-and-Opportunity-Management-Guide-Jan-2017.pdf
3. DHS Probabilistic Risk Analysis and Terrorism Risk: https://www.dhs.gov/xlibrary/assets/rma-risk-assessment-technical-publication.pdf
4. Probabilistic Structural Risk Assessment and Risk Management for Small Airplanes: https://www.tc.faa.gov/its/worldpac/techrpt/ar11-14.pdf
5. FAA Risk Management Handbook: https://www.faa.gov/sites/faa.gov/files/2022-06/risk_management_handbook_2A.pdf
6. EPA: https://www.epa.gov/risk/use-monte-carlo-simulation-risk-assessments
7. NIST
    a. https://www.nist.gov/risk-management
    b. https://nvlpubs.nist.gov/nistpubs/legacy/sp/nistspecialpublication800-30r1.pdf
    c. https://nvlpubs.nist.gov/nistpubs/ir/2021/NIST.IR.8286A.pdf
    d. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=932609
8. https://www.irs.gov/pub/irs-soi/05stephenson.pdf
9. https://bja.ojp.gov/program/psrac/basics/what-is-risk-assessment
10. OMB Circular No. A-123, Management's Responsibility for Enterprise Risk Management and Internal Control – https://www.osec.doc.gov/opog/privacy/Memorandums/OMB_Circular_A-123.pdf
11. The National Library of Medicine contains an array of publications that rely on Monte Carlo analysis. One example is a paper by J. Concato and A. R. Feinstein from the Department of Medicine, Yale University School of Medicine, titled "Monte Carlo methods in clinical research: applications in multivariable analysis." The conclusion of this research was summarized as: "Monte Carlo techniques offer attractive methods for

clinical investigators to use in solving problems that are not amenable to customary mathematical approaches." Monte Carlo methods in clinical research: applications in multivariable analysis – PubMed (nih.gov)

12. R. Harrison in the Department of Radiology at the University of Washington: Introduction To Monte Carlo Simulation – PMC (nih.gov)
13. The National Institute of Science and Technology created an open source "NIST Uncertainty Machine" which is an "R" application to evaluate overall measurement uncertainty for many input variables with associated statistical distributions, available on GitHub at GitHub – usnistgov/NIST-Uncertainty-Machine.
14. As an example of application of the NIST Uncertainty Machine, this publication describes the use of the machine to characterize uncertainty in calculation of the gas constant using the ideal gas law, where mass, pressure, and temperature all have measurement uncertainties: Monte Carlo Uncertainty Propagation with the NIST Uncertainty Machine | Journal of Chemical Education (acs.org)

Additionally, any statistical analysis developed by NTIA should rely upon some level of standardization to ensure consistent modeling and results. NTIA should develop a process to allow for the filing and public availability of non-sensitive data needed to model the RF environment. Collaborative discussions with all affected stakeholders, including federal agencies, commercial wireless parties, and the FCC are necessary to ensure that any statistical analysis methodology is appropriate and sufficiently accurate. Moreover, this standardization process could allow for normalizing of the data or field measurements to confirm the accuracy of the underlying simulation modeling. Examples of use of standardization include:

- DoD Data Strategy, https://media.defense.gov/2020/Oct/08/2002514180/-1/-1/0/DOD-DATA-STRATEGY.PDF
- Army Data Plan, https://www.army.mil/article/246361/army_data_quality_improved_through_standardization_and_collaboration

D. Improving Propagation Modeling.

Propagation modeling is an ever-evolving field of study being pursued by both industry and government. Commercially, CapEx efficient network deployments require accurate modeling of signal propagation over the target environment, which may be rural, suburban, or urban and with variations of natural and human-made structures that can affect propagation. From a governmental perspective, policies and regulations are in part driven by signal types and geographies, and some systems rely critically on an accurate understanding of coverage or impact areas of a system. NTIA should engage in measurements, using either internal resources or third-party services, of the RF environment to improve and inform propagation modeling, giving priority to portions of the 5-16 GHz frequency range.

Accurately modeling the characteristics of signal propagation is critical to the results of the simulation, as the propagation conditions greatly affect the resulting signal characteristics at a receiver. The physical characteristics of the signal path are also affected by atmospheric conditions, terrain, trees or other foliage, buildings, building materials, structures (such as bridges, street signs, light posts, etc.), and the density of these features, which are collectively referred to as clutter. These physical features cause ducting, diffraction, reflection, multipath, and other channel impairments that will impact the propagation loss and could vary significantly with time. The physical aspects of the environment, transmitters, and receivers should be modeled in three dimensions.

Experts from industry and government recognize that existing propagation models have limitations. "One size fits all" approaches to propagation modeling do not work well because the physical environment, frequencies in use, and systems under consideration vary drastically. This leads to a conclusion that, despite advances in modeling, radio science is non-deterministic and probabilistic uncertainties will remain.

More work is needed to address these concerns. Currently, existing models require users to be experts who understand the constraints and limitations of a propagation model and its simulation inputs for a valid answer or range of answers to be obtained. Instead of relying on an individual's experience, an expert system or handbook would be useful to recommend an appropriate model and dataset to a given situation.[10] This would also help with standardization/consistency of models for particular situations/use cases, approach, and processes. NTIA, under a DoD-sponsored effort, is undertaking a mid-band propagation modeling project that is focused on improving modeling within the 3.5 GHz band to support spectrum sharing and coexistence.[11] Additionally, NTIA has been working with commercial wireless providers to obtain real-world measurements of 5G systems to confirm the accuracy of propagation modeling. NTIA could work with ITS and other interested stakeholders to extend these efforts from the 3 GHz band all the way to 16 GHz.

The complexity of the systems under consideration needs to be modeled in sufficient detail and with a range of variations to accurately represent the system to the point at which the outputs of simulations reflect their sensitivity to the inputs. However, modeling the entire range of possible inputs is impractical for a complex system, and thus models that focus on narrowly defined cases are likely to be more accurate than general models. Further, as environments become more complex and policymakers consider frequencies at a higher range, additional study is needed to develop accurate models.

Measurement of the RF environment is crucial to tuning and validating propagation models. This is especially important in air-ground scenarios, over long distances and ranges of altitude, in complex environments, at higher frequencies, and under non-line of sight conditions, where collectively the propagation modeling field has less experience. Measurement of the RF environment requires accurate collection systems and careful planning for locations of measurements, especially airborne environments. With advances in software defined radios, ease of use of software apps for planning driving routes, and availability of high-resolution terrain data, commercial approaches to widespread data collection are now available and could be considered. Priorities for data collection and measurement should be driven by public policy questions plus industry's need for better information to improve and validate propagation models. Where possible, data structures should conform to open-source measurement databanks

[10] For example, ITU-R SG3 has published such a handbook that could be utilized by NTIA. In addition, ITS has also developed a number of models that could be applied for radar coexistence modeling as appropriate for the frequency range of interest.

[11] *See e.g.*, https://winnf.memberclicks.net/assets/Proceedings/2022Virtual/WInnComm%202022%20Propagation%20Modeling.pdf.

and use standardized collection methods—so that all parties are utilizing standardized, validated models for coexistence analyses. NTIA should establish a working group that includes NTIA, FCC, and all interested federal Agencies and industry stakeholders to tune and validate propagation modeling in the 5-16 GHz frequency range using the measured data NTIA has collected.

E. Possible NTIA Approaches for Coexistence Efforts.

Coexistence between federal agency use of the spectrum and commercial entities in the 5-16 GHz frequency range will necessitate a process to coordinate between NTIA, FCC, and industry and federal users prior to implementation of any technical rules and, as discussed above, a process to allow for iterations of coexistence modeling as a better understanding of how the wireless networks are deployed. The underlying data associated with those federal and non-federal deployments can be provided to NTIA and the FCC for coexistence studies, with appropriate protections for proprietary and sensitive data, while working toward as much transparency as is feasible. Once the coexistence studies have been conducted, NTIA should ensure that there is a transparent process with the federal agencies with the radar mission responsibility to receive feedback on the analysis prior to any final decision on coexistence. In general, NTIA should work with the FCC to attempt to model the potential use of the spectrum by commercial entities, as discussed above, well in advance of any FCC rulemaking action. NTIA should interact with any affected federal agency during this process to ensure that each different agency, with its own particular requirements for protection and mission, is conferred with and allowed an opportunity to provide feedback for the coexistence analysis. Results from these technical efforts should be used to inform any Notice of Inquiry or Proposed Rulemaking activity by the FCC to incorporate the findings from those studies. While collaboration between NTIA and FCC has occurred in many instances, an agreement to create a systematic process in each instance would benefit all affected stakeholders and should be implemented by NTIA.

Based on these findings, and following the completion of a rulemaking process, NTIA should work with the FCC to incorporate the necessary technical parameters and protections into the FCC rules. Commercial wireless licensees will need to abide by these restrictions within the FCC's rules, but NTIA should consider development of a process that would allow for changes to the limits based on new technical information about operating characteristics and deployment features (highlighted above) and determine if such changes would occur in perpetuity or would be time limited. Further, NTIA should reevaluate the necessity for new changes over time. These types of changes would be contemplated in the FCC's rules but must be approved by NTIA in consultation with the affected federal agencies. Moreover, such a process should be bidirectional—federal agencies should similarly have the opportunity to seek changes to adjust their operations over time as well. However, NTIA, in cooperation with the FCC, should set a certain level of protection for coexistence between spectrum users—and any parameter changes sought by federal agencies or commercial users that maintain that level of protection would not require additional action, other than notification to NTIA and all affected parties. However, should either federal or non-federal entities decide that changes to their operating systems may cause changes to the level of protection, NTIA should consider developing a process that allows revisiting of the agreement (that is public and includes all federal/non-federal stakeholders). This will allow all parties to have the flexibility to modify their systems over time without introducing wholesale changes to the operating environment.

NTIA should consider leveraging past approaches to develop a transparent process for coexistence analyses. The following are some of the past practices that could be studied:

1. PATHSS effort to study coexistence between non-federal and Department of Defense use of the 3.1-3.45 GHz band.[12]
2. CBRS ongoing coordination efforts, including use of the Telecommunications Advanced Research and Dynamic Spectrum Sharing System (TARDyS3).[13]

V. ROLE OF NTIA IN ENSURING INDEPENDENT AND TIMELY ANALYSIS OF INTERFERENCE SCENARIOS.

NTIA's role in ensuring independent and timely analysis of interference scenarios may be constrained by the authorities and processes for US spectrum management. The US has established a national organizational structure for radio spectrum management based on bifurcated authorities (the FCC and NTIA), with their governance focused not on parts of the radio spectrum or specific radio services but on the constituent groups that they oversee. NTIA oversees federal agency spectrum use while the FCC oversees essentially any radio user and operation outside the federal government agencies. The processes that these two agencies use to coordinate the use of spectrum within the United States, including allocation of spectrum to radio services, are the result of statutory authorities[14] and cooperative agreement between the agencies.[15] For example, the US Table of Frequency Allocations is maintained by the FCC and is changed through public rulemakings, but the outcomes of such rulemakings that involve government spectrum users are, at least in part, based on agreements reached between the FCC and NTIA. Via an MOU in place since the 1940s and most recently updated in 2022, the two agencies have set forth processes for coordinating any decision or intended decisions that might impact the users under the other spectrum authority (although this coordination arrangement in no way changes the separate authorities).[16] The 2022 MOU states that the FCC and NTIA "will engage . . . in engineering collaboration" and, when commenting on each other's public proceedings, will endeavor to provide "contributions supported by relevant technical data and analysis based on sound engineering principles . . . . of a quality that complies with best engineering practices and any mutually agreed standards or procedures."[17]

Questions concerning the independence of analysis performed by NTIA and the FCC stem from what may be their perceived roles as the advocates for their constituent groups. Statutes governing the FCC and NTIA require them to consider the national perspective, not merely that of their constituent groups. However, public perception and the perception among spectrum users may be that the FCC is the advocate for non-federal entities and NTIA is the advocate for federal entities, while it also has the mandate to promote commercial wireless.

[12] *See e.g.*, https://insidedefense.com/insider/dod-backed-consortium-launches-new-mid-band-spectrum-task-group.
[13] *See e.g.*, https://www.fcc.gov/document/new-tardys3-portal-and-list-protected-facilities-35-ghz-band.
[14] *See, e.g.,* 47 U.S.C. §§ 901-903, 922.
[15] *See, e.g.,* 47 U.S.C. §§ 301-303, 305, 309(j).
[16] *MOU Between the FCC and NTIA on Spectrum Coordination* (Aug. 2, 2022), https://docs.fcc.gov/public/attachments/DOC-385867A1.pdf (2022 MOU) (direct download).
[17] *Id.* at 4.

Recent Administrations have prioritized evidence-based policy decisions rooted in the best available science and data, stating that, "when scientific or technological information is considered in policy decisions, it should be subjected to well-established scientific processes, including peer review."[18] These have been government-wide policy, not specific to spectrum policy.

The Office of Management and Budget (OMB) has provided guidance, developed in consultation with the Office of Science and Technology Policy (OSTP), titled, "Final Information Quality Bulletin for Peer Review."[19] The Department of Commerce has committed to "implement evidence-based decision making within the Department of Commerce to increase program and policy impact."[20] Scientific peer review could help enable evidence-based policymaking in spectrum management, as there are increasingly hard decisions due to congestion and incompatibility.

A shared understanding of the technical data is the foundation of evidence-based policymaking. However, the first obstacle encountered in the coordination of a spectrum study is a lack of shared technical understanding. One way to enable shared technical understanding is by leveraging open-source coexistence analysis and data transparency.

Non-federal users seek to achieve their spectrum goals through the FCC's rulemaking and authorization processes but may also seek support through advocacy before Congress and through national political leaders within federal departments and agencies as well as the White House. Non-federal entities also express their views directly to NTIA regarding aspects that may impact federal users and engage directly with impacted federal spectrum users. Federal spectrum users work through NTIA, which has been designated as the agency through which the Administration speaks to the FCC. Thus, rather than federal agencies expressing their views on spectrum issues directly to the FCC, Congress, or other outlets available to non-federal users, NTIA gathers federal inputs via its Interdepartment Radio Advisory Committee (IRAC), evaluates those views and prepares the Administration's position on FCC proposals. NTIA may choose a different course than that recommended by the agencies' technical analysis and concerns. The FCC sits in meetings of the IRAC, so it is always aware of pending decisions by NTIA and inputs from the agencies. NTIA monitors public FCC processes on spectrum allocation, but also receives drafts of FCC decisions for review in accordance with the NTIA/FCC MOU, and the Administrator and FCC Chair are directed to engage in quarterly meetings under that same MOU.

When conflicts cannot be resolved at the staff level, coordination and negotiation can continue in the Policy and Plans Steering Group (PPSG). This body brings executive leadership together from the agencies and the FCC, but also includes OSTP and OMB (bodies not otherwise engaged in IRAC activities). Some issues are taken outside these established bodies and are worked through leadership at NTIA, the FCC, the White House (primarily OSTP/NSC/NEC), and the specifically impacted agencies.

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[18] *See e.g.*, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/memorandum-on-restoring-trust-in-government-through-scientific-integrity-and-evidence-based-policymaking.
[19] *See* https://www.federalregister.gov/documents/2005/01/14/05-769/final-information-quality-bulletin-for-peer-review.
[20] *See* https://www.commerce.gov/about/strategic-plan.

In considering NTIA's role to ensure independent and timely analysis, the federal agencies realize that NTIA will ultimately present to the FCC the Administration's views/analysis and any agency views/analysis must be accepted by NTIA. This leads to the concern that an agency's ability to deliver on its mission requirements can be affected by NTIA, a separate agency with no statutory authority over that mission. At the same time, NTIA is located within the Department of Commerce. Therefore, NTIA goals and priorities reflect Administration policy goals, which is not necessarily synonymous with agency missions. Rather than focus on how NTIA can contribute to "independent" interference analysis, it may be best to focus on how NTIA can contribute to "inclusive" interference analysis. NTIA cannot be separated from the agencies as NTIA's role includes managing federal use of spectrum; furthermore, NTIA ensures that agencies' views on telecommunication matters are effectively presented to the FCC. However, NTIA can seek to be technical, thorough, accurate, and fully inclusive of concerned party inputs to any analysis and related spectrum decision. One of the more significant challenges is the comparatively deep level of understanding of commercial wireless technology and how wireless networks use spectrum that exists, versus the myriad technologies in federal systems broadly – whether ground-based, space-based, or aviation-based, and the associated concept of operations which is how missions are in fact delivered.

Clearly, NTIA must ensure that agencies' statutorily authorized missions are taken into account, including the expert agency views as it tries to conduct spectrum interference analyses. Under the current governance model, the agencies have limited avenues to present their concerns outside of the PPSG or IRAC, filing directly with the FCC, or raising issues to the Congress or the White House.[21] Thus, if NTIA is to ensure independent analysis, it must partner with the federal agencies to ensure that the technical and operational requirements of the agencies are reflected in the work of the technical staff in OSM and ITS to develop technical analysis methods. NTIA must also seek to engage with and facilitate technical discussions between non-federal parties and the concerned agencies. Detailed and direct technical collaboration between federal and non-federal users can often lead to well-constructed technical analyses and the use of those analyses in determination of coordinated technical solutions.

Therefore, the CSMAC views the critical steps for NTIA to perform "independent" or what may better be referred to as "inclusive" analyses to be:

- Increase staff to ensure understanding of mission requirements, not just technical RF. Explore a program similar to the program run by the FCC that details independent agency employees throughout the executive branch.
- Development, coordination, and implementation of recognized and accepted analysis tools and techniques (including risk-informed interference analysis) via OSM's focused engineering staff supplemented by ITS.
- Understanding each agency's method to analyze technical and operational issues.
- Ensuring full representation of agency views, concerns, and analyses, as appropriately modified by NTIA expert inputs to present one coordinated Administration view via NTIA that avoids federal agency direct filings to the FCC.

[21] *See* https://www.ntia.doc.gov/files/ntia/publications/csmac_sc1_report_july_2020_r1.pdf.

- Where feasible, facilitation of direct discussions between non-federal and federal groups to work out fully vetted and agreed technical analysis methods and sharing or coordination arrangements that are based on those analysis methods.

The most recent version of the NTIA/FCC MOU appears to encourage this approach:

> *(5) The FCC and the NTIA commit to improved and effective communication on matters that relate to the management of the nation's spectrum resource. (a) The staffs of FCC and the NTIA will engage, on an ongoing basis, in engineering collaboration to, for example, identify best practices, develop metrics for effective spectrum analysis, and examine technologies to enhance spectrum use. (b) To facilitate evidence-based spectrum policymaking, in particular when participating in each other's public proceedings, the FCC and the NTIA will endeavor to do so on a timely basis through contributions supported by relevant technical data and analysis based on sound engineering principles, including available test and receiver performance data, where appropriate. Such information will be of a quality that complies with best engineering practices and any mutually agreed standards or procedures. (c) The FCC and the NTIA will endeavor to provide relevant and appropriate information, including, but not limited to, the nature of federal and non-federal operations and uses of spectrum in their spectrum coordination communications, ensuring appropriate treatment of any sensitive and classified information. The FCC and the NTIA will also identify, as early in the decision-making processes as possible, any technical issues that have a reasonable likelihood of generating disputes or disagreements and will act in their capacities as the sole agencies responsible for managing spectrum use in the United States to further assess such issues.*
>
> *(6) The FCC and the NTIA will resolve technical, procedural, and policy differences by consensus whenever possible.*
>
> *(7) The staffs of the FCC and the NTIA will cooperate to develop and implement a process through which evidence-based concerns of either agency about harmful interference posed by a proposed final action by the FCC or the NTIA can be escalated. If such concerns cannot be resolved between NTIA's Associate Administrator for Spectrum Management and the FCC's Chief of the Office of Engineering and Technology, the matter may be referred to the Assistant Secretary of Commerce for Communications and Information and the FCC Chair for consideration before final action.*[22]

Although these processes cover many of CSMAC's recommendations for inclusive analysis, the MOU does not explicitly mention the facilitation of direct discussions or collaboration between the concerned federal and non-federal user communities. CSMAC suggests that this may be a critical point for improvement.

For NTIA's inclusive analysis efforts to be useful, they also need to be timely. One should note that the text in the MOU paragraph (5)(b) cites the need for timely participation. However, the thoroughness of any analysis depends in part on the time allowed for the analysis. Short timeframes allow only simple and probably worst-case analysis. Some analyses may

[22] 2022 MOU at 4.

require development and agreement of new methods. Sometimes, measurements become part of the solution to validate analysis results or to input into the analysis data. Greater lead-times can allow for the user collaboration outlined above. Greater lead-times also make possible higher-level interactions of concerned parties that may be necessary to negotiate agreement. As stated in the MOU paragraph (6), the goal is a consensus outcome. Among the concerned user groups, a consensus can be the difference between a smooth implementation of spectrum decisions and the kinds of public objections raised to political levels recently experienced.

The allowance for agency responses to draft FCC decisions under the NTIA/FCC MOU reads:

> *(3) The FCC will cooperate with the NTIA and endeavor to give notice of all proposed actions that could potentially cause interference to federal operations, including operations in adjacent spectrum allocations. Where possible, such notice will be given in time for the NTIA to comment prior to final action and a minimum of 20 business days prior to final action. The FCC will endeavor to give NTIA the same notice and opportunity to comment, in instances in which NTIA notifies the FCC that non-federal operations critical to federal agency missions, including those essential to national security or safety of life, could potentially experience harmful interference from a proposed action. A different review period may be agreed to by NTIA's Associate Administrator for Spectrum Management and the FCC's Chief of the Office of Engineering and Technology. Where applicable, FCC staff will endeavor to engage NTIA staff in discussions regarding NTIA's comments on the FCC action. Final action by the FCC, however, does not require approval of the NTIA.*
>
> *(4) The NTIA will cooperate with the FCC and endeavor to give notice of all proposed actions that could potentially cause interference to non-federal operations. Where possible, such notice will be given in time for the FCC to comment prior to final action and a minimum of 20 business days prior to final action. A different review period may be agreed to by NTIA's Associate Administrator for Spectrum Management and the FCC's Chief of the Office of Engineering and Technology. Where applicable, NTIA staff will endeavor to engage FCC staff in discussions regarding FCC's comments on the NTIA action. Final action by the NTIA, however, does not require approval of the FCC.*[23]

The 20 working days allowance, while longer than that allowed under previous versions of the MOU and stated as a minimum, is generally taken as the limit for NTIA to provide a coordinated response. This date can be viewed as the time allowed for NTIA to express an inter-agency coordinated concern. Thus, a concern expressed by NTIA in that time may be sufficient to buy more time for a thorough analysis. However, 20 days is generally not sufficient time to actually develop and perform a complex technical analysis or supporting measurements that may be required to substantiate any concerns and to engage the actual federal operators beyond the agency spectrum offices. Moreover, should testing be required, this timing can extend to months to gather this type of data. This is especially true for federal spectrum users, which can have multiple, dissimilar systems to model and protect.

[23] *Id.* at 3.

Complex analyses, supported by new or modified models and supporting measurement and the kind of desirable federal/non-federal collaboration toward consensus described above can take many months (even assuming all necessary technical and operational details are complete and available). The 20-day period stated in the MOU deals with the view of a draft decision document developed after significant input from affected stakeholders in a rulemaking proceeding. Best practices would be for both agencies to identify potential issues much earlier in the spectrum decision process. Therefore, the identification of potential issues should be included in NTIA/FCC staff discussions envisioned by the MOU and discussed before a Notice of Proposed Rulemaking is adopted. Furthermore, given the formal requirements of the administrative processes for FCC rulemakings, the FCC and NTIA will need to consider paths to federal/non-federal user collaboration early as issues are developed during the notice-and-comment process, as opposed to when conflicts are identified in draft final rules.

Last, as noted in the MOU paragraph (7), a path to raise issues up the political chain needs to be taken when conflicts cannot be resolved. The MOU specifically cites interaction between the NTIA Administrator and the FCC Chairman; however, the PPSG is a forum that can discuss these issues with executives across agencies and includes representatives from OSTP, OMB, NSC, and NEC.

VI. ENFORCEMENT.

Interference can occur, whether in a shared spectrum environment or an exclusive use environment. Interference can occur for many reasons, including emissions from incidental radiators, a breakdown in a sharing mechanism, a malfunction in a transmitter, or intentional modification of authorized equipment parameters by a bad actor. Interference degrades or obstructs to varying degrees the proper operation of a communications system. Harmful interference to safety-of-life and certain other systems may require a rapid and decisive response.

While some spectrum users maintain some internal capabilities to deal with interference incidents, statutory authority for investigation of violations of the Communications Act and subsequent enforcement actions involving non-federal operations rests with the FCC, regardless of whether the interference is into federal users. The FCC's resources for *ex post* enforcement activities to support the detection, classification/identification, location, reporting, mitigation, and remediation of (harmful) interference incidents have declined from past years and are extremely limited. Reasonable assurance of protection of federal and non-federal systems in a shared-spectrum environment requires robust mechanisms to identify and mitigate interference. Both CSMAC and the FCC TAC have produced various recommendations in this regard.[24] In addition, NTIA, in collaboration with the FCC, should develop penalties for entities that fail to abide by the coexistence agreements.

The subcommittee recommends that:

- NTIA should work with the FCC and federal/non-federal user communities to help develop capabilities for *ex post* enforcement activities (in addition to *ex ante* protection), such as budget requests that include reference to the FCC specifying costs to support federal agency enforcement/protection needs as coexistence between

[24] *See e.g.*, https://www.ntia.doc.gov/files/ntia/publications/csmac_enforcement_subcomm_recommendations_111717.pdf. *See also* https://www.fcc.gov/oet/tac/tacdocs/reports/2016/A-Study-to-Develop-a-Next-Generation-System-Architecture-V1.0.pdf.

federal and non-federal spectrum users continues to expand.

- NTIA, together with the FCC, should develop and identify enforcement processes necessary to ensure compliance with spectrum coexistence arrangements. Time periods for resolving interference issues should be developed. NTIA should identify and facilitate sharing of federal agency resources (e.g., specialized FAA aircraft, US Coast Guard vessels, specialized equipment at ITS) to improve the efficiency and effectiveness of data gathering for enforcement activities.
- NTIA should work with the FCC to establish penalties for failing to comply with the coexistence agreement requirements.

VII. CSMAC RECOMMENDATIONS

In accordance with the direction received from NTIA, the following recommendations are provided to suggest improvements in electromagnetic coexistence compatibility studies between non-federal terrestrial and federal aeronautical operations in the 5-16 GHz frequency range. The recommendations are not meant to be used with any other services in this frequency range, or in any other bands.

RECOMMENDATION 1: Coexistence Collaboration Process. The CSMAC recommends that NTIA, in coordination with the FCC, set as a routine step early in the spectrum decision making process a mechanism for direct industry (providers and manufacturers) and government user collaboration for the development and coordination of tools and techniques for any portions of the 5-16 GHz frequency range.

RECOMMENDATION 2: Statistical Models/Analysis. The CSMAC recommends that NTIA, in collaboration with the FCC and federal and non-federal user/stakeholder communities, develop guidelines for the use of statistical models/analysis for coexistence studies for any portions of the 5-16 GHz frequency range, make those guidelines available to the public, and apply those guidelines to analyses performed as the first stage of coexistence studies. Such modeling and analysis should account for different agencies/commercial industries having very different metrics for defining the risk of interference.

RECOMMENDATION 3: Data Transparency. The CSMAC recommends that NTIA develop a process to allow for the filing and public availability of non-sensitive data needed to model the radiofrequency environment for the 5-16 GHz frequency range.

RECOMMENDATION 4: Coexistence Analysis Updates. The CSMAC recommends that NTIA, in coordination with the FCC and federal and non-federal user communities, establish a process or processes for updating coexistence arrangements in any portions of the 5-16 GHz frequency range as federal and non-federal operations, systems and technologies continue to evolve.

RECOMMENDATION 5: Risk Measures. The CSMAC recommends that NTIA translate interference in the radiofrequency realm into risk measures. A risk measure could be defined as the tolerance for interference that a particular system could manage. Risk measures could be used to model the statistical likelihood of harmful interference and based on the government-determined tolerance for risk (including degradation and/or disruption) for the spectrum user under study within the 5-16 GHz frequency range. Risk also includes the ability or lack thereof to adopt innovative, next generation capabilities in either commercial or federal missions under coexistence arrangements.

RECOMMENDATION 6: Propagation Model Improvements. The CSMAC recommends that NTIA engage in measurements of the RF environment to improve and inform propagation modeling to enable coexistence analysis between aeronautical radar and commercial wireless services in the 5-16 GHz frequency range.

RECOMMENDATION 7: Propagation Model Working Group. The CSMAC recommends that NTIA should establish a working group that includes NTIA, FCC, and any interested federal agencies and industry stakeholders to tune and validate propagation modeling discussed in Recommendation 6 for the 5-16 GHz frequency range using the measured data NTIA has collected.

RECOMMENDATION 8: Inclusive Analysis. The CSMAC recommends that NTIA ensure full representation of agency views, concerns, and analyses to present one coordinated view that avoids federal agencies needing to supplement publicly the record of their views through direct filings to the FCC, and where feasible, facilitate direct discussions between non-federal and federal entities to work out fully vetted and agreed technical analysis methods and sharing or coordination arrangements that are based on those analysis methods.

RECOMMENDATION 9: Interference Mitigation. The CSMAC recommends that NTIA work with the FCC and the federal/non-federal user and OEM communities to identify resources or mechanisms to locate and accurately and expeditiously mitigate harmful interference that may be experienced in coexistence environments within any portion of the 5-16 GHz frequency range. (For example, resources and mechanisms could be provided through user community funding).

RECOMMENDATION 10: Enforcement of Coexistence Arrangements. The CSMAC recommends that NTIA, together with the FCC, develop and identify enforcement activities and mechanisms necessary to ensure compliance with spectrum coexistence arrangements in any portion of the 5-16 GHz frequency range.

RECOMMENDATION 11: Compliance Penalties. The CSMAC recommends that NTIA should work with the FCC to establish penalties for failing to comply with the coexistence agreement requirements.

APPENDICES

Appendix I: Use of Risk Analysis by Federal Agencies

Risk analysis and management is a well-established and accepted science.[25] Applying risk analysis and management to spectrum interference analysis is a novel application of a well-established field. Risk analysis can inform decision makers on the range of risks, including their likelihood (typical, maximum, unpredictable, etc.) and impact (e.g., minimum, harmful interference) of spectrum decisions.

Federal agencies and other organizations have established and use a wide variety of risk analysis techniques to manage their risk. For targeted analysis these organizations utilize statistical risk-based analysis to analyze the probability and impact of events that, if realized, could threaten outcomes. Monte Carlo simulation is a commonly employed statistical technique that uses repeated random sampling to present a distribution of possible outcomes, accounting for uncertainty and variability, rather than a single point estimate.

This section highlights statistical risk analysis used by certain Federal agencies, including the Environmental Protection Agency (EPA), Department of Defense (DoD), Department of Homeland Security (DHS), Federal Aviation Administration (FAA), National Institute of Standards and Technology (NIST), Internal Revenue Service (IRS), Office of Management and Budget (OMB), and National Institute of Health (NIH). The summary below is intended to provide a broad view but is not all-encompassing of how these federal agencies conduct risk assessments. Each of these agencies provide multiple types of analytic approaches to assess risk.

The subcommittee is interested in the utility of statistical analytic approaches to address risks to the electromagnetic environment. It is notable that many Federal agencies have documented the utility of Monte Carlo simulations in contrast to other mathematical models. The subcommittee recommends that NTIA review these guidelines and determine if any could be applied to simulations that model the electromagnetic spectrum environment.

A. Environmental Protection Agency (EPA)

EPA has used risk analysis since its early days to assess risks of various stressors to humans and ecosystems.[26] It has published many documents on risk assessment. EPA discusses use Monte Carlo analysis in risk assessments as follows:[27]

> *EPA designed its human health risk assessment guidance (e.g., EPA, 1991, 1989 and 1988) to produce protective, rather than best, estimates of risk. EPA is aware that true risks are probably less than its estimates, but has chosen a regulatory policy of giving the benefit of uncertainty surrounding the risk assessment to the exposed public.*

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[25] Within the fields of risk analysis and statistics, variability is the amount of divergence of data points from the average value of the data set, i.e., the spread of the data. Uncertainty is the unknown about a future outcome or event that results in lack of or incomplete data. The Environmental Protection Agency discusses uncertainty and variability at https://www.epa.gov/expobox/uncertainty-and-variability#faq1.

[26] https://www.epa.gov/risk/about-risk-assessment.

[27] https://www.epa.gov/risk/use-monte-carlo-simulation-risk-assessments.

These protective risk estimates sometimes create difficulty for Agency decision-makers and the public. Site-specific Regional risk assessments usually present risk as a single number, or single-point estimate, accompanied by a qualitative discussion of uncertainty. The public tends to focus on the single-point estimate and to overlook the uncertainty, which may span several orders of magnitude. EPA risk managers, though aware of the uncertainty, must still justify their decision to either accept or reduce the single-point risk. If the risk is close to the maximum acceptable level, it is likely that different assumptions would have produced a different risk number, leading to a different decision. In this way, single-point risk assessment methods place the risk assessor in an inappropriate risk management role.

Recent EPA guidance on risk characterization (EPA, 1992) discusses this problem in depth, and recommends the use of multiple risk descriptors in addition to protective single-point risk estimates. Inclusion of these additional risk descriptors provides the public with more complete information on the likelihood of various risk levels, and risk managers with multiple risk-based cleanup goals from which to choose. This guidance mentions Monte Carlo simulation as an effective source of multiple risk descriptors.

EPA also acknowledges the following limitations of Monte Carlo simulations:[28]

1. *Available software cannot distinguish between variability and uncertainty. Some factors, such as body weight and tap water ingestion, show well-described differences among individuals. These differences are called "variability". Other factors, such as frequency and duration of trespassing, are simply unknown. This lack of knowledge is called "uncertainty". Current Monte Carlo software treats uncertainty as if it were variability, which may produce misleading results.*

2. *Ignoring correlations among exposure variables can bias Monte Carlo calculations. However, information on possible correlations is seldom available.*

3. *Exposure factors developed from short-term studies with large populations may not accurately represent long-term conditions in small populations.*

4. *The tails of Monte Carlo risk distributions, which are of greatest regulatory interest, are very sensitive to the shape of the input distributions.*

Monte Carlo analysis is not recommended as the only or primary method of risk analysis but, rather, that "uncertainty and variability surrounding single-point risk estimates rely on multiple descriptors of risk (EPA, 1992). Monte Carlo simulation will be an acceptable method for developing these multiple descriptors."[29]

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28 *Id.*
29 *Id.*

B. Department of Defense (DoD)

The "DoD Cost Estimating Guide" defines risk and opportunity:[30]

> *A risk is a potential future event or condition that may have a negative effect on cost, schedule, and/or performance. An opportunity is a potential future event or condition that may have a positive effect on cost, schedule, and/or performance.*

DoD cost estimating models generally address uncertainty first. Risks and opportunities are then addressed if not included in the uncertainty assessment. The data collection plan should support the risk and uncertainty analysis.

The "DoD Cost Estimating Guide" summarizes multiple methods to address risk and uncertainty. Simulation (inputs-based) is one technique "to approximate the probability of certain outcomes by executing multiple trial runs." It further notes:[31]

> *Simulation is often referred to as 'Monte Carlo.' In fact, Monte Carlo is but one way to develop a string of random numbers, the heart of the simulation method. There are many others; Latin Hypercube may be the most popular.*
>
> *In addition to uncertainty, the cost model needs to have methods to estimate the impact of discrete risk/opportunity events, risk mitigation plans identified by the program office, and proposed opportunity initiatives. Risk/opportunity events are situations that result in an impact to the project performance, cost, or schedule if they occur. Therefore, a risk/opportunity event has three characteristics: a definable situation, a probability that situation will occur, and a consequence should the event occur. If the consequence is negative to the program it is a risk. If the impact is positive, it is an opportunity.*

The "Department of Defense Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs" notes that Monte Carlo methods "may be used in simulation models to find the cumulative effect of multiple risks."[32]

C. Department of Homeland Security (DHS)

DHS undertook an effort to build "an Integrated Risk Management Framework to improve its capability to make risk-informed strategic decisions using systematic and structured assessments of homeland security risk." It defines probabilistic risk assessment as:[33]

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[30] https://www.cape.osd.mil/files/Reports/DoD_CostEstimatingGuidev1.0_Dec2020.pdf cites DoD, Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs, 2017, para. 1.1, "Purpose", pg. 3.

[31] https://www.cape.osd.mil/files/Reports/DoD_CostEstimatingGuidev1.0_Dec2020.pdf.

[32] https://acqnotes.com/wp-content/uploads/2017/07/DoD-Risk-Issue-and-Opportunity-Management-Guide-Jan-2017.pdf.

[33] https://www.dhs.gov/xlibrary/assets/dhs_risk_lexicon.pdf.

A type of quantitative risk assessment that considers possible combinations of occurrences with associated consequences, each with an associated probability or probability distribution.

Probabilistic risk assessments are typically performed on complex technological systems with tools such as fault and event trees, and Monte Carlo simulations to evaluate security risks and/or accidental failures.

Probabilistic and decision analysis applications have been examined as potential approaches to analyze terrorism risk.[34]

D. Federal Aviation Administration (FAA)

With the FAA mission to "provide the safest, most efficient aerospace system in the world," the FAA uses a safety management system (SMS) to integrate safety risk management into operations, acquisition, rulemaking, and decision making. SMS includes safety policy, safety risk management (SRM), safety assurance, and safety promotion.

The FAA's national "Safety Risk Management Policy" establishes requirements for how to conduct SRM. SRM includes the system description, identification of hazards, and analysis and controlling safety risk. It is critical to both the design and development of equipment and procedures as well as evaluating safety in the operational environment. The FAA analyzes safety risk as follows:[35]

The safety risk of a hazard is the function of the severity and likelihood of the hazard's potential outcomes. The safety risk associated with the hazard must be determined and documented in terms of severity and likelihood.

Severity is the potential consequence or impact of a hazard in terms of degree of loss or harm. It is a prediction of how bad the outcome of a hazard can be. There may be many outcomes associated with a given hazard, and the severity should be determined for each outcome.

Likelihood is the estimated probability or frequency, in quantitative or qualitative terms, of the outcome(s) associated with a hazard. It is an expression of how often an outcome of a hazard is predicted to occur in the future. When sufficient empirical data exists, statistical probabilities should be used.

The FAA's "Risk Management Handbook" provides recommended tools and training to the pilot in command to identify, assess, and manage hazards to perform the safest flight possible. It provides a pilot, aircraft, environment, and external pressures (PAVE) checklist. Once risks are identified, the likelihood (probability) and severity (consequences) of a particular outcome are analyzed. A tabular matrix may be used to assess the composite of these two parameters. The FAA has a flight risk assessment tool (FRAT) that uses a spreadsheet to capture numerical and

[34] https://www.dhs.gov/xlibrary/assets/rma-risk-assessment-technical-publication.pdf.
[35] https://www.faa.gov/documentLibrary/media/Order/FAA_Order_8040.4B.pdf.

narrative hazards. Additional FAA tools – including the consequences, alternatives, reality, and external pressures (CARE) checklist and detect, estimate, choose, identify, do, and evaluate (DECIDE) – can be used to process and analyze risks in accordance with the perceive, process, and perform (3P) risk analysis system. The 3P model was developed by FAA to help pilots make decisions during all phases of flight.[36]

The FAA report on "Probabilistic Structural Risk Assessment and Risk Management for Small Airplanes" provides a probabilistic risk assessment methodology for analyzing and managing the risk of structural fatigue-failure issues. Probabilistic modeling of the critical variables is used due to significant airplane-to-airplane and flight-to-flight variations. It uses Monte Carlo analysis to predict the risk of failure and associated sensitivities. The methodology is incorporated into the FAA's Small Aircraft Risk Technology (SMART) software.[37]

E. National Institute of Standards and Technology (NIST)

Risk management underlies NIST's cybersecurity and privacy work. As such, it has partnered with stakeholders to develop a suite of risk management standards and guidelines.[38]

NIST's "Integrating Cybersecurity and Enterprise Risk Management (ERM)" includes qualitative and quantitative analysis methods. Quantitative analysis can include values based on statistical probabilities. The report provides example techniques for estimating the probability that a risk will occur. These techniques include:[39]

> *Bayesian Analysis – A model that helps inform a statistical understanding of probability as more evidence or information becomes available*
>
> *Monte-Carlo – A simulation model that draws upon random sample values from a given set of inputs, performs calculations to determine results, and iteratively repeats the process to build up a distribution of the results*
>
> *Event Tree Analysis – A modeling technique that represents a set of potential events that could arise following an initiating event from which quantifiable probabilities could be considered graphically*

NIST's "Guide for Conducting Risk Assessments" describes fundamental concepts, the process for conducting risk assessments, and communicating and sharing results. The appendix includes a description of likelihood and impact. It specifies that it defines likelihood as a score, rather than a statistical function.[40]

"Identifying and Estimating Cybersecurity Risk for Enterprise Management" explains risk guidance, identification, and analysis and provides examples of risk tolerance, risk appetite and methods to assess risk. This NIST report illustrates statistical analysis, including level of

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36 https://www.faa.gov/sites/faa.gov/files/2022-06/risk_management_handbook_2A.pdf.
37 https://www.tc.faa.gov/its/worldpac/techrpt/ar11-14.pdf.
38 https://www.nist.gov/risk-management.
39 https://nvlpubs.nist.gov/nistpubs/ir/2020/NIST.IR.8286.pdf.
40 https://nvlpubs.nist.gov/nistpubs/legacy/sp/nistspecialpublication800-30r1.pdf.

confidence to represent uncertainty. It includes sections on three-point estimation, event tree analysis, Monte Carlo simulation, and Bayesian analysis. The report applies risk analysis to the Cybersecurity Risk Management (CSRM) domain and concludes:[41]

> *While statistical analysis has been available for hundreds of years, many within the CSRM community have only recently recognized the value of applying a more quantitative approach to risk estimation. It seems likely that those in the CSRM domain will continue to develop and improve statistical methods to estimate risk and include guidance regarding the application of various statistical distribution models.*

As another example, the US National Security Agency (NSA) and NIST funded a paper on a "Model-Based Risk Analysis Approach for Network Vulnerability and Security of the Critical Railway Infrastructure." This paper models the threat, vulnerability, and risk management within the critical railway infrastructure. As described in the paper:[42]

> *After modeling the system architecture and network topology, risk analysis tools are used for automatically propagating the risk values, and visualization tools are used to visually inspect the component attack trees of specific component risks and system attack graphs that also consider how risks can propagate across components via their network interconnections. In addition, our automated risk assessment tool can analyze all the modeled system vulnerabilities, evaluate them for their impact on overall system-level risk, and rank order them for targeting mitigation actions against most damaging vulnerabilities. We also provided a novel approach to handle dynamic network connections for analyzing risks amidst changing network topology of infrastructure components, such as mobile locomotives and its on-board devices in the railway transportation systems. The quantitative approach to risk analysis and model-based design and automated analysis tools provides a highly powerful framework for analyzing risks of critical infrastructures, such as a railway transportation system. It is important to note that the algorithms and approaches developed in this work are equally applicable to other types of critical infrastructures.*

Because NIST found value in Monte Carlo simulations, it released in the open source its NIST Uncertainty Machine, which is an application to evaluate measurement uncertainty.[43] An example of the use of the NIST Uncertainty Machine is described in a publication on "Monte Carlo Uncertainty Propagation with the NIST Uncertainty Machine."[44]

F. Internal Revenue Service (IRS)

In an effort to increase compliance of small business and self-employed taxpayers, the IRS developed a Risk-Based Collection Model that included techniques such as tree-based classification, neural network models, logistic regression, and cluster analysis. It applied

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[41] https://nvlpubs.nist.gov/nistpubs/ir/2021/NIST.IR.8286A.pdf.
[42] https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=932609.
[43] GitHub - usnistgov/NIST-Uncertainty-Machine: Uncertainty propagation tool using both Gauss formula and monte carlo method.
[44] https://pubs.acs.org/doi/10.1021/acs.jchemed.0c00096.

machine learning to use historic data to generate models for prediction, forecasting, estimation, and decision support. Results of the collection strategy and model indicate more effective collection of tax revenue.[45]

G. Office of Management and Budget (OMB)

OMB Circular No. A-123, "Management's Responsibility for Enterprise Risk Management and Internal Control," was published to help federal agencies manage risks to achieving their strategic objectives. The circular discusses establishing enterprise risk management (ERM) in management practices and setting up and operating an effective system of internal control.[46]

H. National Institute of Health (NIH)

NIH's National Library of Medicine contains an array of publications that rely on Monte Carlo analysis. One example is a paper, "Monte Carlo Methods in Clinical Research: Applications in Multivariable Analysis." The conclusion of this research was summarized as: "Monte Carlo techniques offer attractive methods for clinical investigators to use in solving problems that are not amenable to customary mathematical approaches."[47]

Another relevant paper on Monte Carlo simulation, "Introduction To Monte Carlo Simulation," summarizes the history of Monte Carlo simulation and discusses the method, including techniques used in the field of medical imaging.[48]

[45] https://www.irs.gov/pub/irs-soi/05stephenson.pdf.
[46] https://www.osec.doc.gov/opog/privacy/Memorandums/OMB_Circular_A-123.pdf.
[47] https://pubmed.ncbi.nlm.nih.gov/9291696.
[48] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2924739/#:~:text=Monte%20Carlo%20simulation%20uses%20random,the%20operations%20of%20complex%20systems.

Appendix II: Application of Risk Analysis to Electromagnetic Compatibility Improvements

Current risk adverse spectrum sharing approaches are inefficient and could be improved with additional risk analytics that inform risk sharing policies and approaches. These approaches will result in minimization of interference on most critical users while permitting acceptable levels of interference for other users. Introducing risk tolerance into spectrum sharing will improve electromagnetic compatibility by enabling more users to utilize the same spectrum efficiently and effectively.[49]

Essential to enacting risk informed sharing that is based on risk tolerance requires identifying the most critical users. Multiple methods can be utilized to determine the most critical users including ranking, market mechanisms, and assessment criteria. A higher criticality represents users or systems that if disrupted would have a higher operational impact. Users or systems with lower criticality will have little operational impact. Regardless of the methodology used to determine the most critical users, this information allows operators that are sharing spectrum to enact policies and techniques that minimize interference on those critical users.

Defining risk informed sharing policies and techniques also requires a clear understanding of the amount of possible interference in a given area. Defining the types of users in the electromagnetic operating environment will enable modeling of the possible interference that users can cause for each other and collectively. Simulations (e.g., Monte Carlo analysis) can be used to determine the possible distribution of the level of interference that a given type of user may experience. Translating interference (e.g., signal-to-noise ratio) into probability of disruption or degradation facilitates the assessment of risk.

In Figure 1 below the charts are an example of statistical interference analysis. The first chart is a sample model of multiple networks moving through a particular electromagnetic operating environment. The second and third charts represent a snapshot of when networks cause interference above a particular acceptable threshold. The outputs from interference analysis can be translated into a probability of disruption or degradation.

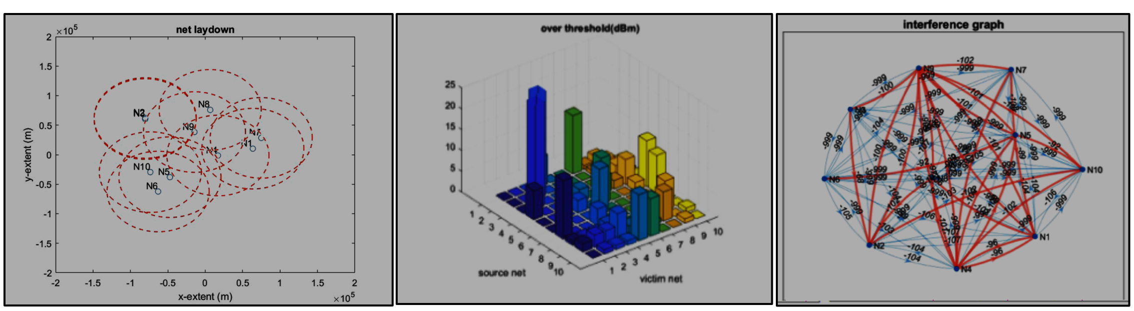

Figure 1. Example of Statistical Interference Analysis Translated into Probability of Disruption

[49] https://its.ntia.gov/media/jqjc0cat/henry_isart22_risk-informed-spectrum-sharing-and-management-capability.pdf.

Once the range of possible interference and the probability of disruption or degradation is determined, a value function can be defined to translate interference levels into a standardized risk scale. Value functions reflect the overall risk tolerance with high risk indicating that interference prevents the user from being able to utilize the spectrum to execute their intended use and low risk indicating that there is no interference to intended use. Value functions can vary in nature from simple step functions to more complex forms.

Figures 2 and 3 are examples of value functions translating a probability of disruption into a risk score measure. In Figure 2, there are five different value functions that vary based on the criticality of the spectrum user. For a high critical spectrum user (Level 5) a probability of disruption above 50% would be considered high risk. For a spectrum user with lower criticality (Level 3) the probability of disruption would have to be above 72% to be considered high risk. The value functions reflect the risk tolerance of the users and can support prioritization of spectrum resources through policies and spectrum sharing schemes to minimize risk to the highest priority users while allowing some risk (and thus higher interference).

Risk	Mission Criticality Level - Probability of Disruption Ranges																							
Level	Level 5					Level 4					Level 3					Level 2					Level 1			
H	>=	50	<	100	H	>=	60	<	100	H	>=	72	<	100	H	>=	86	<	100	H	>=	95	<	100
MH	>=	40	<	50	MH	>=	48	<	60	MH	>=	58	<	72	MH	>=	69	<	86	MH	>=	76	<	95
M	>=	30	<	40	M	>=	36	<	48	M	>=	43	<	58	M	>=	52	<	69	M	>=	57	<	76
LM	>=	20	<	30	LM	>=	24	<	36	LM	>=	29	<	43	LM	>=	35	<	52	LM	>=	38	<	57
L	>=	0	<	20	L	>=	0	<	24	L	>=	0	<	29	L	>=	0	<	35	L	>=	0	<	38

Figure 2. Example of Value Function Translating Probabilities into Risk Measures based on Criticality (Higher Criticality indicates higher operational impact)

Value functions can vary in form as shown in Figure 1 and 2. Figure 1 represents a classic step function whereas Figure 2 provides a series of distributions that can be used to translate the probability of disruption into a risk score measure. In Figure 2, the leftmost distribution represents a low risk tolerance where the risk level rises quickly with a low probability of disruption. The rightmost distribution represents a high-risk tolerance where the probability of disruption must get high before any increase in the level of risk. The leftmost distribution would be used for critical spectrum users that cannot tolerate interference and disruption. The rightmost in contrast reflects a very high tolerance for interference and disruption for that spectrum user.

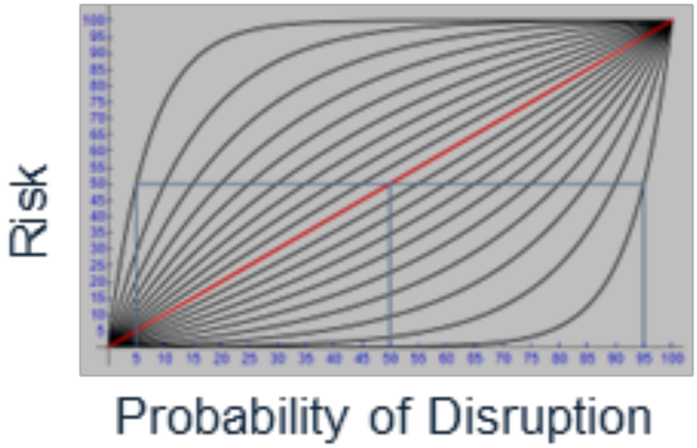

Figure 3. Example of Value Functions Translating Statistical Analysis into Risk Measure (Different curves can be selected for different criticality levels). The curve selected reflects the risk tolerance of interference.

Risk score measures represent the potential level of operational impact that a given disruption may cause. Risk models can model full disruption as well as various levels of degradation. Each one of these will result in different value functions.

Translating interference into risk measures allows optimization of the use of spectrum by minimizing the risk to the most critical users. Policies, techniques, and rules can be tested to understand the level of risk different users experience. Multiple optimization methods can be used when conducting these evaluations.

Appendix III: Federal Airborne and Other Radar Systems Operating in the 5-16 GHz frequency range

Radar Name	Bands / Freqs.	Agency	Description	Operations & Mission	Technical Parameters	Additional Information
5250-5925 MHz						
Multiple	5250-5255 MHz	Military	The radar systems operating in the 5250-5255 MHz band are primarily used by the military. These military radars have the operational capability to tune across the entire 5250 - 5725 MHz frequency range. The military radars that operate in this band include both target search and tracking radars that can use a single frequency or can employ frequency hopping techniques across the entire band. In the past, these radars have been limited to operating on or near military installations. However, there may be situations where the military uses these radars in support of homeland security.			https://www.ntia.doc.gov/files/ntia/publications/compendium/5250.00-5255.00_1Feb2017.pdf

Radar Name	Bands / Freqs.	Agency	Description	Operations & Mission	Technical Parameters	Additional Information
Poseidon-3 Radar Altimeter	5250-5255 MHz	NASA & NOAA	NASA and NOAA have been tracking global ocean surface topography with joint ocean altimeter satellite and spacecraft missions from an orbit 1336 km above the ocean surface utilizing SAR. The Poseidon-3 altimeter emits pulses at two frequencies 13.6 and 5.3 GHz to measure the distance from the satellite to the surface (range). Free electrons in the atmosphere can delay the signal's return, affecting the measurement accuracy. The delay is directly related to the radar frequency, so the difference between the two measurements can be used to determine atmospheric electron content.	The satellite/spacecraft radar altimeters measure the precise distance between the platform and sea surface. Measures sea level, wave heights and wind speed.		https://www.ntia.doc.gov/files/ntia/publications/compendium/5250.00-5255.00_1Feb2017.pdf https://sealevel.jpl.nasa.gov/missions/ostm-jason-2/spacecraft-and-instruments/
Airborne Radar and Associated Airborne Beacon	5350-5470 MHz (Two segments: 5350-5460 & 5460-5470 MHz)	FAA, DoD Commercial	Commercial: (secondary) Weather Radar & Airborne Radar	The military services operate numerous radars in the 5250–5925 MHz band in support of national and military test range surveillance and instrumentation operations; airborne radar transponders; battlefield missile surveillance and tracking; weather radar observations; shipborne fire-control of surface-to-air missiles; shipborne surface search radars; shipborne missile and gunfire-control radar; and navigational aids to assist in precise positioning of ships.		https://www.ntia.doc.gov/files/ntia/publications/compendium/5350.00-5460.00_1Feb2017.pdf

Radar Name	Bands / Freqs.	Agency	Description	Operations & Mission	Technical Parameters	Additional Information
Several	5350-5460 MHz	DoD	The band is used extensively for test range instrumentation radars to track rockets, missiles and other targets. In addition, DoD uses this band for radars that are part of an advanced ground-based air defense missile system. The Navy uses a shipborne radar system and its variations for surface search and navigation. This includes a wide range of range and target acquisition requirements.			
Terminal Doppler Weather Radar (TDWR)	5600-5650 MHz	FAA	TDWRs are used to detect wind shear and other weather conditions near airports. Also called NEXRAD and WSR-88.	TDWR presently is the only radar that FAA operates in this band. The band is shared with various weather radars operated by the DOD, NWS, and commercial weather radar systems usually associated with local new television stations. Operates at 45 major airports around the nation to provide wind shear and other critical weather data to air traffic controllers supporting safe flight operations.	Tx Pwr (peak): 310 kW Tx Pwr (avg): 550 W Emission: 35M00P0N	https://www.faa.gov/air_traffic/weather/tdwr https://www.ncei.noaa.gov/products/radar/terminal-doppler-weather-radar
Airborne Phased Array Radar (APAR) (Future)	5350-5450 MHz	NOAA	Airborne Phased Array Radar (APAR) is an advanced atmospheric system being developed in part to replace the expired, X-band Electra Doppler radar (ELDORA). Preliminary design specifications suggest the proposed APAR will meet or exceed ELDORA's sensitivity, spatial resolution and Doppler measurement accuracies and it will also acquire dual-polarization measurements.	APAR, currently under design by NCAR/EOL, consists of four removable C-band Active Electronically Scanned Arrays (AESAs) mounted on the top, both sides, and the cargo ramp of the NSF/NCAR C-130 aircraft. Each AESA is approximately 1.8 m x 1.8 m in size and is made up of ~2,400 transmitting/receiving antenna elements with dual-polarimetric capabilities. The dual-polarimetric capabilities of APAR, in addition to inherent beam agility associated with electronic steering, will provide more flexible scanning strategies and enhanced measurement capabilities.	Tx Pwr (peak): 14.3 kW	https://www.eol.ucar.edu/instruments/airborne-phased-array-radar-apar

Radar Name	Bands / Freqs.	Agency	Description	Operations & Mission	Technical Parameters	Additional Information
8.5-10.0 GHz						
AN/TPY-2 Surveillance Transportable Radar	8500-10000 MHz	Army	Air Surveillance Radar.	The AN/TPY-2 is a missile-defense radar that can detect, classify, and track ballistic missiles. Also part of Terminal High Altitude Area Defense (THAAD) network.		
Airborne Doppler Radar	8750-8850 MHz	FAA	Airborne Doppler navigation aids on a center frequency of 8800 MHz. Doppler Navigation is a self-contained aircraft navigation system developed in the 1940s that uses Doppler effect radar interaction with the earth in dead-reckoning calculations to navigate.	Today it is used mostly in rotary aircraft – helicopters. It was also used in commercial fixed-wing aircraft initially for several years, including secondary navigation support in some military planes, before being replaced by global positioning system (GPS) navigation. Doppler navigation systems transmit four frequency-modulated continuous-wave radar beams directed downward at about 45 degrees, fore and aft, at 8,800 MHz.	RTCA DO-158: Standards and test procedures for Airborne Doppler Radar Navigation Equipment	https://www.baesystems.com/en-us/definition/what-is-doppler-navigation
Airport Surface Detection Equipment-X (ASDE-X)	9000-9200 MHz	FAA	Airport Surface Detection System — Model X (ASDE-X) is a surveillance system using radar, multilateration and satellite technology that allows air traffic controllers to track surface movement of aircraft and vehicles. It was developed to help reduce critical Category A and B runway incursions.	The airport surface detection equipment (ASDE) is a radar that maps the airport surface to provide information to the controller concerning aircraft on the ground as well as certain vehicular traffic within the airport.	Tx Pwr (peak): 4.5 kW Tx Pwr (avg): 3 W Emission: 4M00P0NAN	https://www.faa.gov/air_traffic/technology/asde-x
Air Traffic Navigation, Integration and Coordination System (ATNAVICS)	9000-9200 MHz	Army	The AN/TPN-31 Air Traffic Navigation, Integration and Coordination System (ATNAVICS) is a highly mobile, self-contained, tactical Airport Surveillance Radar (ASR) and Precision Approach Radar (PAR) system that provides Air Traffic Service (ATS) at designated airfields and landing sites.			

Radar Name	Bands / Freqs.	Agency	Description	Operations & Mission	Technical Parameters	Additional Information
Multimode Survivable Radar	9200-10500 MHz	Army				
Airborne Radar and Associated Airborne Beacon	9300-9500 MHz	FAA				
Garmin GWX 68 GWX 70 GWX 80	9300-9500 MHz	FAA, Commercial	Airborne Doppler Weather Radar.	Airborne Wx radar used to help pilots identify and avoid thunderstorms, other precipitation and wind shear.		https://www.garmin.com/en-US/c/aviation/general/weather-radar-receivers/
Rockwell Collins RTA-4100 Hazard Detection System	9450-9490 MHz (9461-9476 GHz)	FAA, Commercial	Airborne Doppler Weather Radar.	Airborne Wx radar used to help pilots identify and avoid thunderstorms, other precipitation and wind shear.	Tx Pwr (peak): 50W BW: 32 MHz Min. Detectable Signal: -126 dBm	https://prd-sc101-cdn.rtx.com/-/media/ca/product-assets/files/public/products/product-brochures/radar-and-surveillance/weather-radar/rta-4100-multiscan-data-sheet.pdf?rev=d3909408022a4d67b764f90edc9867fb&hash=9824A9F9B0EACF960570A25E67B25A4B
Rockwell Collins RTA-4218	9450-9490 MHz (9456-9481 GHz)	FAA, Commercial	Airborne Doppler Weather Radar.	Airborne Wx radar used to help pilots identify and avoid thunderstorms, other precipitation and wind shear.	Tx Pwr (peak): 40-150W	
Rockwell Collins ISS-2100 Integrated Surveillance System	9320-9400 MHz	FAA, Commercial	Airborne Doppler Weather Radar.	Airborne Wx radar used to help pilots identify and avoid thunderstorms, other precipitation and wind shear.	Tx Pwr (peak): 40-150W	https://www.collinsaerospace.com/what-we-do/industries/commercial-aviation/flight-deck/surveillance/integrated-surveillance/iss-2100-configurable-integrated-surveillance-system
Rockwell Collins WXR-2100 Weather Radar	9327-9348 MHz	FAA, Commercial	Airborne Doppler Weather Radar.	Airborne Wx radar used to help pilots identify and avoid thunderstorms, other precipitation and wind shear.	Tx Pwr (peak): 40-150W	https://www.collinsaerospace.com/what-we-do/industries/commercial-aviation/flight-deck/surveillance/weather-radar/wxr-2100-multiscan-threat-track-weather-radar

Radar Name	Bands / Freqs.	Agency	Description	Operations & Mission	Technical Parameters	Additional Information
Tail Doppler Radar (TDR)	9315 MHz	NOAA	The Tail Doppler Radar is a vertically scanning, pulse Doppler radar installed on the tail of research aircraft. The original instrument, designed by NOAA and NCAR, was tested on NOAA aircraft and has since expanded to multiple platforms. This X-band radar with a magnetron transmitter has a scan rate of either five or ten rotations per minute and a corresponding range gate of 150 or 300 meters.	The Tail Doppler Radar system is located at the back end of the aircraft. As the plane flies through a storm, the TDR continuously measures near-vertical cross-sections of precipitation and winds. By piecing together all of these cross-sections, scientists are then able to create a three-dimensional image of the storm. This three-dimensional "CAT scan" can show where the strongest winds are, how far the strong winds extend out from the storm center, and where the most intense rainfall occurs. The TDR is mounted on Gulfstream IV and Lockheed P-3 aircraft.	Tx Pwr (peak): 8-60 kW Antenna Gain (dB): 36.5-40.0 Min Detectable Signal: -111 dBm	https://www.aoml.noaa.gov/real-time-doppler-radar/ https://www.aoml.noaa.gov/hrd/about_hrd/HRD-P3_radar.html

Radar Name	Bands / Freqs.	Agency	Description	Operations & Mission	Technical Parameters	Additional Information
Electra Doppler Radar (ELDORA)	9300-9800 MHz	NOAA, NASA	ELDORA is an airborne, dual beam, meteorological research radar developed jointly by NCAR and France's Centre de Recherches en Physique de L'Environnement Terrestre et Planetaire (CRPE), France. ELDORA mounts on a Lockheed P-3 aircraft. Its two antennas extend back from the tail of the aircraft and spin about the longitudinal axis of the aircraft. One antenna points slightly ahead of the aircraft and one slightly aft. The ELDORA radar system consists of five major functional blocks: the RF signal generator/receiver unit, the TWT high power amplifiers, the signal processor, the antenna/rotodome system, and the radar control equipment. Since the radar system consists of two separate fore- and aft- pointing radars much of the hardware contains two identical modules. Only the basic signal generation equipment and the radar control equipment do not contain duplicate modules.	ELDORA's mobility allows observations of clouds, convective systems and storms over remote regions. As the aircraft translates the antennas through space ELDORA traces two conical helixes through the atmosphere, essentially observing all of the atmosphere with two separate looks within 50-100 kilometers of the aircraft.	Tx Pwr (peak): 35-40 kW Antenna Gain (dB): 39 Rx BW: 1.5-4.0 MHz	https://www.eol.ucar.edu/observing_facilities/electra-doppler-radar-eldora
Interferometeric SAR	9456.5–9749.5	Army	The Interferometric Synthetic Aperture Radar - Elevation (IFSARE) was developed by Environmental Research Institute of Michigan (ERIM), Ann Arbor, Mich., under a Defense Advanced Research Projects Agency (DARPA) project.	IFSARE uses interferometric radar on an ERIM-owned LearJet 36A to collect and record data, then process it on the ground into digital terrain elevation models.		https://cpb-us-w2.wpmucdn.com/sites.gatech.edu/dist/5/462/files/2016/08/AESS-IFSAR-Tutorial.pdf

Radar Name	Bands / Freqs.	Agency	Description	Operations & Mission	Technical Parameters	Additional Information
New airborne scientific radar under development by BAE Systems Information and Electronic Systems Integration Inc.	9300-9500 MHz [FCC Experimental License 0099-EX-ST-2023]	NASA	Demonstrate scientific capabilities to NASA and NOAA.	Used to construct a 3-dimensional representation of precipitation and winds below the aircraft to study various weather phenomena such as convective precipitation and tropical cyclones, as well as providing data to improve and validate satellite precipitation estimates (NASA Global Precipitation Measurement (GPM) Mission).		
NASA ER-2 X-band Doppler Radar (EXRAD)	9600 MHz [NASA125538], 9620 MHz [NASA125539]	NASA	Dual-beam Doppler radar.	Used to construct a 3-dimensional representation of precipitation and winds below the aircraft to study various weather phenomena such as convective precipitation and tropical cyclones, as well as providing data to improve and validate satellite precipitation estimates (NASA Global Precipitation Measurement (GPM) Mission).		
13.25-16.0 GHz						
Airborne Doppler Radar	13.25-13.4 GHz	FAA				
NASA 2nd Generation Airborne Precipitation Radar (APR-2) [SPS-18056/1, SPS-18762/1]	13405 MHz [NASA123023] and 35605 MHz [NASA123022]	NASA	Dual-frequency, dual-polarization, Doppler radar.	Used to construct a 3-dimensional representation of precipitation below the aircraft including classification and velocity of precipitation particles (with cross-track scanning).		
NASA 3rd Generation Airborne Precipitation Radar (APR-3) (identical to the APR-2 with the addition of W-band sensor)	13405 MHz [NASA123023], 35605 MHz [NASA123022], and 94920 MHz [NASA983026]	NASA	Tri-frequency, dual-polarization, Doppler radar.	Used to construct a 3-dimensional representation of precipitation below the aircraft including classification and velocity of precipitation particles (with cross-track scanning).		

Radar Name	Bands / Freqs.	Agency	Description	Operations & Mission	Technical Parameters	Additional Information
NASA Snow Water Equivalent Synthetic Aperture Radar and Radiometer (SWESARR) [SPS-23910/1, SPS-24291/1)	9650 MHz [NASA165504], 13600 MHz [NASA215568], and 17250 MHz [NASA215564]; passive sensors: 10600-10700 MHz [NASA215565], 18600-18800 MHz [NASA215566], and 36000-37000 MHz [NASA215567]	NASA	Tri-band synthetic aperture radar (SAR) and tri-band radiometer.	Used to measure land surface snow depth and remotely determine the resulting water content within the snowpack (Snow Water Equivalent (SWE)).		
NASA Hi Altitude Imaging Wind and Rain Airborne Profile (HIWRAP) Radar [SPS-17635/3, SPS-18427/2]	13400 MHz [NASA125540], 13750 MHz [NASA125541], 33400 MHz [NASA125542], 35500 MHz [NASA125543]	NASA	Dual-frequency, dual-beam, Doppler radar system.	Used to image winds through backscattering from clouds and precipitation enabling it to measure the tropospheric winds above heavy rain at high levels.		
Airport Surface Detection Equipment-3 (ASDE-3)	15.7-16.2 GHz	FAA			Emission: 28M0P0N	
Airport Surface Detection Equipment-2 (ASDE-2)	24.45-24.65	FAA				