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Spectrum Issues Faced by Active Remote Sensing

Radio frequency interference and operational restrictions

Message from FARS Technical Committee Chairs Sidharth Misra and Paolo de Matthaeis

One of the main objectives of the Frequency Allocations in Remote Sensing (FARS) Technical Committee (TC) has been to inform IEEE Geoscience and Remote Sensing Society members of the increasing spectrum challenges faced by the remote sensing community. In the June 2014 issue of *IEEE Geoscience and Remote Sensing Magazine*, we presented an overview of spectrum allocations and radio frequency interference management techniques for passive remote sensing. This article, prepared by FARS-TC members, summarizes the impact of interference on active remote sensing systems. If you are interested in contributing or learning about issues such as these, please contact the chairs of the FARS-TC.

The scientific users of radio frequencies must contend with the fact that the spectrum is becoming increasingly crowded, which is in large measure due to the advent of advanced affordable electronics and mobile wireless technology. The growing demand for bandwidth has sparked increased discussions in the microwave remote sensing community of how to respond to this crowded spectrum environment and how to deal with the consequent issues of radio frequency interference (RFI). The National Research Council (NRC) published a study in 2010, "Spectrum Management for Science in the 21st Century" [1], that examined the increasing difficulties encountered by passive microwave measurements in the presence of the expanding worldwide commercial and governmental occupancy of the radio spectrum. The challenges faced by passive sensors also have been summarized in a 2014 *IEEE Geoscience and Remote Sensing Magazine* article [2]. Recognizing that active microwave sensors also face spectrum-related issues, NASA later commissioned the NRC to perform a similar study, "A Strategy for Active Remote Sensing Amid Increased Demand for Radio Spectrum," which was recently published in July 2015 [3]. (In this article, the report will be abbreviated as the NRC Active Sensing Report.) This report addresses the spectrum issues faced by active science sensors, primarily radars, and makes recommendations to government, industry, and the remote sensing community going forward. The report considers multiple types of active sensors including ground-based operational weather radars, ionospheric sensing radar, and radar astronomy. This article focuses on spectrum topics related primarily to Earth remote sensing from aircraft and spacecraft.

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THE USE OF THE RADIO SPECTRUM BY ACTIVE SENSORS

Active remote sensing—with its unique ability to investigate geophysical phenomena by exploiting the amplitude, range delay, Doppler shift, and phase changes in the reflected signal—is employed in a variety of earth science disciplines by a growing number of nations. These disciplines include atmospheric science, weather prediction, oceanography, climate studies, cryospheric monitoring, terrestrial ecology, hydrology, seismology, as well as disaster assessment applications. The choice of frequency for a given medium to be sensed (i.e., land, water, or atmosphere) is dictated by the nature of the wave-medium interaction associated with the target as well as the transmission properties of any intervening medium, such as the atmosphere for land remote sensing. Active Earth remote sensing is currently employed at frequencies as low as a few megahertz and as high as hundreds of gigahertz and at many frequencies in between. For example, low RF frequencies (i.e., long wavelengths)

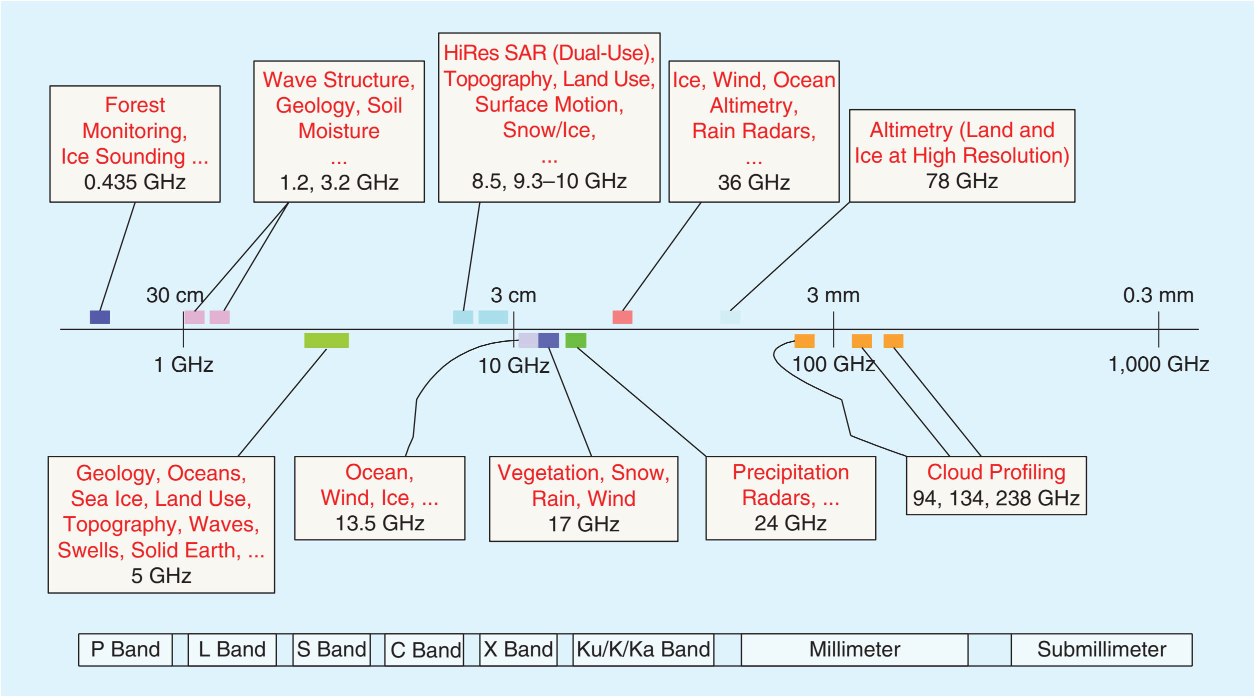

FIGURE 1. The choice of frequencies for satellite active sensing is dictated by the physics of the relevant scattering mechanism. Representative, but certainly not exhaustive, examples of the types of measurements used at each frequency are shown. [Figure used with permission from "A Strategy for Active Remote Sensing Amid Increased Demand for Radio Spectrum," courtesy of the European Space Agency (ESA).]

are best suited for applications that require good penetration through ice or vegetation. In contrast, high frequencies (i.e., short wavelengths) are needed for the detection of small microscopic cloud particles (Figure 1).

FREQUENCY ALLOCATIONS

The radio spectrum is used by many types of services, from radio and television broadcasting to wireless phone communication; weather, military, and remote sensing radars; and radio and radar astronomy, among many others. Radio regulations and frequency allocations are developed at both national and international levels. At the international level, regulations are formulated by the Radiocommunication Sector of the International Telecommunications Union (ITU-R). Spectrum allocations for specific uses are established at the World Radiocommunication Conference, which is held every three to four years. Space-based radar remote sensing operates under the Earth Exploration-Satellite Service (EESS/active), and the associated spectrum allocations are shown in Table 1. Within the United States, spectrum oversight of governmental users [such as NASA, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Department of Defense (DoD)] is the responsibility of the National Telecommunications and Information Administration (NTIA), whereas oversight of private sector users is provided by the U.S. Federal Communications Commission (FCC). It is important to note that active sensors typically share allocations with other services, such as communication systems and radiolocation radars. For active systems, it is also important to differentiate between a spectrum allocation, which is basically the divvying up of the spectrum for different uses, and a spectrum assignment, which is the actual permission to radiate at a specific transmit power in a given band over a particular region of the earth. For active sensors, having a spectrum allocation may not entitle a sensor to radiate if that sensor is thought to create harmful interference to other primary users of that spectral band.

The following two constraints that active sensors often encounter are associated with the spectrum allocation and assignment process that governs active sensors:

1) The shared nature of the allocations can produce RFI that can degrade the performance of science sensors.
2) Active science sensors may be denied an assignment or, otherwise, restricted in their ability to transmit as desired.

RADIO FREQUENCY INTERFERENCE

RFI refers to the unintended reception of a signal transmitted by an unrelated source. When an active sensor receives such a signal, the intended science measurement may be corrupted. An active sensor may also act as the source of interference to a communication system, a passive sensing system, or another radar system, which is discussed in the next

RFI REFERS TO THE UNINTENDED RECEPTION OF A SIGNAL TRANSMITTED BY AN UNRELATED SOURCE.

TABLE 1. THE EESS (ACTIVE) FREQUENCY ALLOCATIONS AND SOME SAMPLES OF CURRENT UTILIZATION BY RADAR SENSORS. (FROM "A STRATEGY FOR ACTIVE REMOTE SENSING AMID INCREASED DEMAND FOR RADIO SPECTRUM.")

BAND DESIGNATION	FREQUENCY BAND AS ALLOCATED IN ARTICLE 5 OF THE RADIO REGULATIONS	APPLICATION BANDWIDTHS				
		SCATTEROMETER	ALTIMETER	IMAGER	PRECIPITATION RADAR	CLOUD PROFILE RADAR
P band	432–438 MHz			6 MHz		
L band	1,215–1,300 MHz	5–500 kHz		20–85 MHz		
S band	3,100–3,300 MHz		200 MHz	20–200 MHz		
C band	5,250–5,570 MHz	5–500 kHz	320 MHz	20–320 MHz		
X band	8,550–8,650 MHz	5–500 kHz	100 MHz	20–100 MHz		
X band	9,300–9,900 MHz	5–500 kHz	300 MHz	20–600 MHz		
Ku band	13.25–13.75 GHz	5–500 kHz	500 MHz		0.6–14 MHz	
Ku band	17.2–17.3 GHz	5–500 kHz			0.6–14 MHz	
K band	24.05–24.25 GHz				0.6–14 MHz	
Ka band	35.5–36 GHz	5–500 kHz	500 MHz		0.6–14 MHz	
W band	78–79 GHz					0.3–10 MHz
W band	94–94.1 GHz					0.3–10 MHz
mm band	133.5–134 GHz					0.3–10 MHz
mm band	237.9–238 GHz					0.3–10 MHz

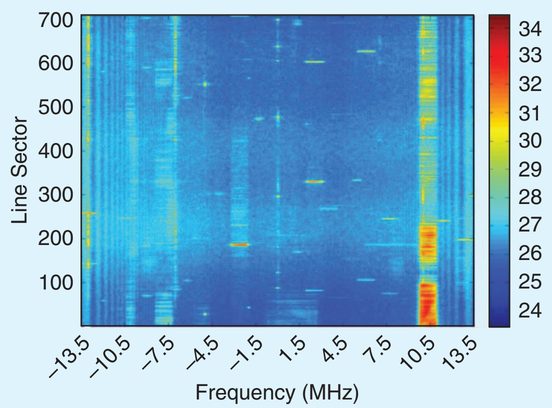

FIGURE 2. A time spectrogram of observed RFI taken from the L-band ALOS/PALSAR mission. The detected power is shown. The horizontal axis is in megahertz from the center frequency, and the vertical axis is the range line number, which corresponds to pulses in time. (Figure used with permission from "A Strategy for Active Remote Sensing Amid Increased Demand for Radio Spectrum," courtesy of NASA/JPL-Caltech and JAXA.)

section. As part of the NRC active sensing study, an assessment of RFI experienced by radar remote sensing receivers was conducted for the bands shown in Table 1. The overall conclusions for the current environment are as follows:

- The lower frequency bands, such as ultrahigh frequency (UHF), P band, and L band, were found to contain significant global interference that has been observed to grow over time. Examples cited in the report include the ground-based European Incoherent Scatter Radar, which ceased operations at 900 MHz after many years of ionospheric studies due to interference from recently deployed telecom services; the interference observed by UHF airborne radars (e.g., the Furgro GeoSAR and NASA AirMOSS) due to the plethora of land-mobile systems; and the steady increase of global L-band interference observed by Japan's series of L-band synthetic aperture radars (SARs) over the past two decades (the JERS-1 mission from 1992 to 1998, ALOS/PALSAR from 2006 to 2011, and the recently launched ALOS-2). A typical time spectrogram manifesting RFI at the L band is shown in Figure 2.
- Users of midfrequency bands, such as the C band and X band, report some interference that may be increasing with time, but the number of incidences has been small to date and limited in geographic location (although, as discussed below, there are significant future threats to these bands). There is an extensive spaceborne data set at the C band beginning in 1991 provided by the ESA's ERS-1, ERS-2, ENVISAT, MetOP, and Sentinel satellites as well as Canada's Radarsat series.
- Active sensing observations at high frequencies (i.e., Ku band and above) appear to be relatively unaffected by RFI. Systems utilizing these frequencies include wind scatterometers, ocean and ice altimeters, and rain/cloud radars flown by a number of space agencies.

The prevalence of RFI at lower radar frequencies has given rise to a variety of RFI detection and mitigation techniques that were developed to correct the data and alleviate the impact on the desired science. There are many techniques that have been developed with the specific strategy function of whether the radar is ground based, airborne, or spaceborne and as a function of the radar center frequency, bandwidth, and application (see [4]–[6] and associated references from *IEEE Transactions on Geoscience and Remote Sensing* special issue on RFI in October 2013). Simply put, RFI is typically detected by identifying the presence of signals different from the expected echo return by their spectral, temporal, or statistical signatures. For example, the presence of a narrowband interferer will appear as a conspicuous spike in the Fourier transform domain, and a pulsed RFI source can be identified by statistically significant jumps in the time domain. Note how both types of interference appear in Figure 2. Also, since radar returns from the surface have Gaussian statistics due to speckle, the presence of RFI may be detected by signal statistics exhibiting non-Gaussian behavior. Once detected, RFI can be removed by filters designed to excise the offending signal while minimizing impact to the desired radar echo. Mitigation techniques work best when the interference has sparse occupancy of the frequency/time domain utilized by the sensor. As more and more frequencies and/or times are impacted by RFI from either a single source or multiple sources, the interfering signals may become more difficult to detect, and mitigation becomes more deleterious to the measurement because more of the desired echo is removed when filtering is applied. In the extreme, a broadband continuous noiselike signal may be impossible to appropriately detect or remove.

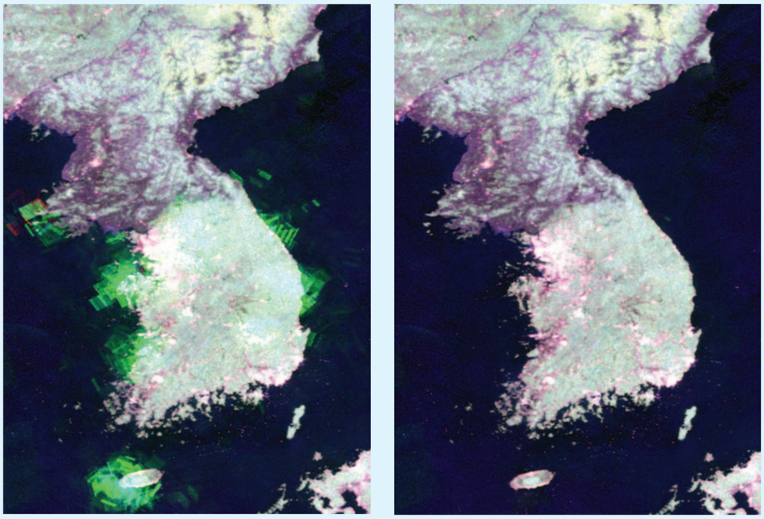
(a) (b)

FIGURE 3. (a) Before and (b) after polarimetric images from the SMAP L-band radar showing the presence of RFI [i.e., the bright green and red marks in part (a)] and the effect of mitigation techniques (b) over the Korean Peninsula. In this region, most RFI observed at the SMAP frequency is pulsed and sparse in time and, consequently, readily removed by filtering. (Images courtesy of NASA/JPL-Caltech.)

Although the current RFI environment, as of 2015, is mostly tolerable due to the application of mitigation techniques when RFI exists, the spectral landscape is continuously evolving. There is growing concern that spectrum pressure for new systems could severely impact remote sensing systems. A high-stakes example is the push by the broadband wireless industry for the addition of the 5,350–5,470-MHz band for radio local area network (RLAN) use. The ESA has studied this issue and has shown that the proposed RLAN deployment will create harmful interference to Sentinel-1 satellites as well as Canada's Radarsat-2 and Radarsat Constellation Mission (three satellites). A major concern is that such an extension of mobile services to the 5,350–5,470-MHz band would eventually be applied worldwide. Studies by the ESA and the Canadian Space Agency suggest that no mitigation would be possible because the aggregated effect of the RLAN RFI is entirely different from that of classical (i.e., pulsed or narrowband) RFI experienced with SAR in that it appears as continuous broadband noiselike interference and, consequently, is distinctively nonsparse in both the frequency and the time domains.

TRANSMIT RESTRICTIONS ON ACTIVE SENSORS

A UNIQUE ASPECT OF ACTIVE SENSORS RELATIVE TO PASSIVE SENSORS IS THAT THEY MAY BE DENIED A FREQUENCY ASSIGNMENT.

As discussed, a unique aspect of active sensors relative to passive sensors is that they may be denied a frequency assignment (or, more commonly, have significant operational restrictions placed on them) if they are perceived as causing interference to existing services. Examples of recently imposed transmit restrictions include the following:

- UHF radars, such as the airborne Fugro GeoSAR interferometric SAR, are required to notch their transmit spectrum to avoid transmitting in specific bands. Over some areas of the United States, the required notching and associated removed bandwidth is so severe as to degrade science performance.
- NASA's Soil Moisture Active Passive (SMAP) radar was obliged to alter its original design to transmit shorter

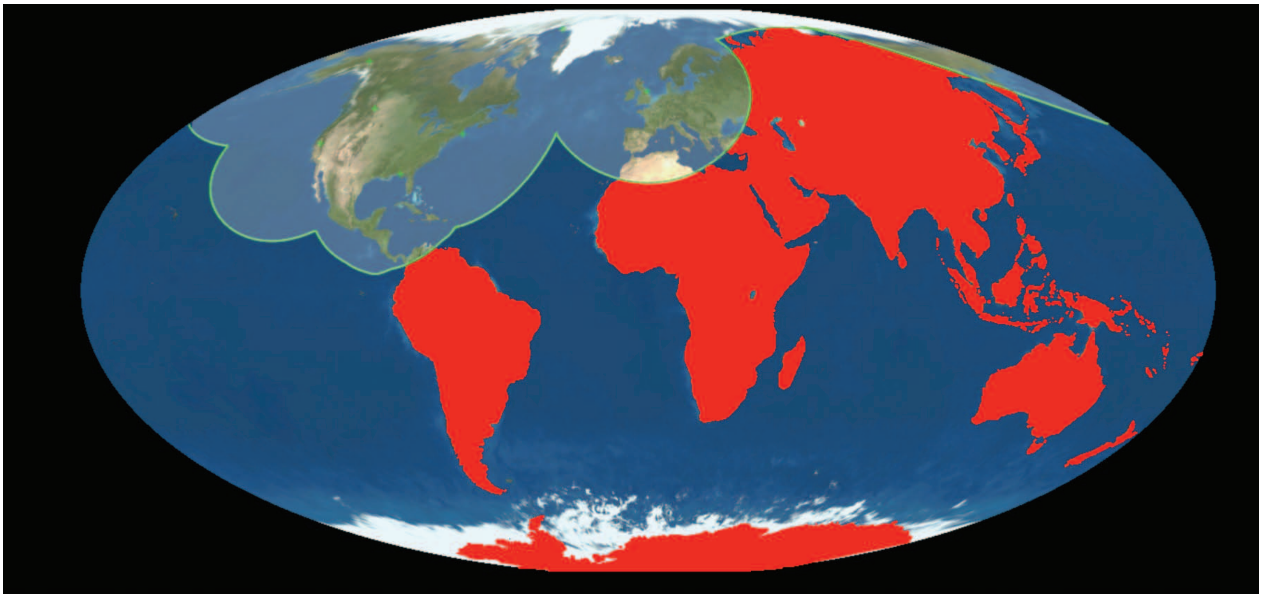

FIGURE 4. The regions of the world to be covered by the P-band European BIOMASS mission are shown in red with the regions of the Northern Hemisphere that will be denied coverage, due to transmit restrictions, are shaded and delineated by green borders. The area of coverage denial is so large because it includes not only the main beam of the BIOMASS antenna but also periods when side lobes of the antenna pattern are in view. (Image courtesy of ESA.)

higher power pulses to minimize the potential interference into long-range air surveillance radars operating at the L band (see Figure 3). The necessary change came late in the development process and at some significant expense to the SMAP project.

- The P-band European BIOMASS mission has been denied permission to transmit within the line of sight of space object-tracking radars located in North America and Europe. Even though the primary mission objectives will still be met with this outage, this will, nevertheless, deprive the community of valuable science data over a significant portion of the globe (see Figure 4). Furthermore, this precedent may negatively impact other potential P-band missions that could target geophysical processes that are important in the Northern Hemisphere, such as root zone soil moisture and ice sheet sounding.

MERIT ALONE WILL NOT ENSURE THAT THE SPECTRUM REQUIRED IS AVAILABLE FOR THE SCIENTIFIC COMMUNITY.

An important finding reported by the NRC Active Sensing Committee is that there are no reported cases where a science sensor has interfered with a non-science service. The committee also found a distinct sentiment in the radar remote sensing community that, in light of such a track record, some of the criteria applied by government spectrum managers in making assignments to science instruments are extremely conservative and that perhaps less stringent allowances should be considered given the societal importance of such measurements. Furthermore, spectrum managers should allow experimental tests to develop new guidelines for conditions under which multiple users can operate without interfering with one another.

RECOMMENDATIONS FOR THE PROTECTION AND EFFECTIVE USE OF THE SPECTRUM REQUIRED FOR ACTIVE REMOTE SENSING

Key recommendations from the NRC Active Sensing Report concerning how to protect and effectively use the spectrum required for remote sensing fall into the following categories: actions by the science community, actions by federal agencies, and possible actions by the telecommunications industry.

ACTIONS BY THE SCIENCE COMMUNITY

Merit alone will not ensure that the spectrum required is available for the scientific community. Scientific interests must be actively represented in the spectrum allocation and assignment process to ensure that science needs are met. This will require ongoing efforts to ensure that active remote sensing is balanced with competing interests in the regulatory processes and to make more information available about the value of active remote sensing.

- The science community should increase its participation in the ITU, NTIA, and FCC spectrum management processes. This includes close monitoring of all spectrum management issues to provide early warning for areas of concern. It also requires regular filings in regulatory proceedings and meetings with decision makers. This will build credibility for the science community to ensure a seat at the table for spectrum-related decision making that impacts the science community.

- For the spectrum management process to be effective, the science community, NASA, NOAA, the National Science Foundation, and the DoD should also articulate the value of the science-based uses of the radio frequency spectrum. Such values will include both economic values, through enabling commerce or reducing the adverse economic impacts of natural phenomena, and noneconomic values that come from scientific research.

ACTIONS BY FEDERAL AGENCIES

The actions of federal agencies responsible for supporting scientific uses of active remote sensing and for overseeing spectrum allocations include the following:

- NASA should lead an effort to significantly improve characterization of the radio frequency interference environment that affects active science measurements. This effort should include the use of modeling, dedicated ground-based and airborne characterization campaigns, and data mining of currently operating scientific sensors. To the extent possible, this effort should be a collaborative one with other space and science agencies of the world.
- NASA should lead a community effort to construct a set of metrics that relates to the various radio frequency interference environments encountered and the associated degradation in science performance for each major class of instruments employed in active remote sensing.
- Radar systems meeting specific criteria for pulse repetition rate, maximum pulse width, and duty cycle should be permitted by the FCC or the NTIA to operate as secondary users in communication bands where minimal interference to the communications operations would be expected to occur.
- NASA should facilitate the possibility of time and frequency sharing between the ESA BIOMASS and the DoD's Space Object Tracking Radar system.

POSSIBLE ACTIONS BY THE TELECOMMUNICATIONS INDUSTRY

- The 50–60-GHz millimeter-wave frequency band includes several subbands already allocated to mobile communications. The use of millimeter-wave frequencies for short-wave femtocell-sized communications would significantly increase network capacity by an order of magnitude, thereby reducing pressure on the spectrum and, therefore, on the active remote sensing users as well.
- The wireless industry should consider pursuing the femtocell approach by developing towers, networks, and the like to add the use of millimeter-wave frequencies for communications in 5G and up.

For a complete set of findings and recommendations of the NRC study, the reader is directed to the full NRC Active Sensing Report.

In conclusion, it is important to point out that committees and institutions, such as the NRC Committee on Radio Frequencies, the Space Frequency Coordination Group, and the IEEE GRSS Frequency Allocations in Remote Sensing Committee, have been advocating for the spectrum needs of the scientific community. With increasing pressure on available spectra, it is crucial for the remote sensing community to support these efforts to address this challenge.

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