THE THREAT TO WEATHER RADARS BY WIRELESS TECHNOLOGY

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When nearby devices transmit at the same frequency as weather radars, the resulting disturbances can severely limit the usefulness of the radar images.

Weather radars work by sending and receiving microwave pulses. When nearby devices transmit at the same frequency, we see the disturbances as dots and spikes in the radar image.

Weather radars work by sending and receiving microwave pulses. The most common microwave frequency ranges for this purpose are S band (2–4 GHz), C band (4–8 GHz), and X band (8–12 GHz), within which certain subbands have been assigned to weather radar on a primary basis. But other players, especially the wireless communication industry, are keen on utilizing the same frequency bands.

When another device is emitting microwaves at the same or nearby frequency as a weather radar, the radar may receive interference, its measurements disturbed, and the output images may manifest typical interference signatures such as dots, spokes, or stripes.

So far a majority of the reported interference cases is from C band, but there is a growing number of cases from S band as well. The latter band is used by radio navigation radars (civilian and military) in addition to weather radars. One of the major agenda items for the recent World Radiocommunication Conference (WRC-15) was to identify more frequency bands for mobile communication, and the 2.7–2.9-GHz band has been under consideration.

This paper is organized as follows: We first explain the nature of the problem, then describe problems experienced in different parts of the world, and finally we assess the attempts to solve the problem.

DETERIORATING QUALITY OF RADAR IMAGES. The microwave pulses transmitted by a radar are scattered from various atmospheric constituents, including raindrops, turbulence, and even insects.

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Although powerful signals (~1 MW) are transmitted, the returned signal from reflection and scattering from such constituents is quite weak (~10^{-10} mW). Within storms and clouds, raindrops are typically 1–5 mm in diameter and spaced 10 cm from each other, so only a small fraction of the transmitted energy hits the drops and, of that energy, only a tiny fraction is scattered back in the direction of the radar antenna. Therefore, weather radar receivers are very sensitive instruments and any disturbance by man-made electronic noise and interference within the same frequency band readily reduces or destroys the usability of the measurements.

A radar measures the distance to the target from the time of arrival of the scattered pulse. When it receives a signal from a device sending a continuous wave (CW), such as telecommunication links, we see a line oriented radially toward the center of the radar image (Fig. 1). If the interfering transmitter is near the radar, we see the disturbance in a sector that can be as much as several tens of degrees wide.

Large raindrops have a stronger effect on horizontally than on vertically polarized microwaves. Hence, single-polarization weather radars tend to use horizontally polarized signals (to maximize rain signals), while the telecommunication industry has preferred vertical polarization (to minimize rain impact). Dual-polarization radars can identify the signals from such radio local area networks (RLANs) and other wireless devices (WDs) from the polarization properties (Keränen et al. 2013; Husnoo and Sugier 2014).

As WD signals have typical, unnatural shapes, it is possible to identify them also by image processing methods (e.g., Peura 2002). If one radial is identified as bad, we can remove it and interpolate weather signal from neighboring radials. (The weather information inside the bad radial is lost.) But when the number of harmful emitters grows, the number of bad radials grows and we have less and less unaffected signals to use for interpolation (Fig. 2).

To a limited extent, it is also possible to identify and eliminate the interference at the signal processing level. Recovering the weak weather signal among strong interfering signals is often/mostly not successful, so there is a fear that this kind of filtering only keeps the problem invisible until the noise level grows to unacceptable levels with the growing number of interferers. Removal of the interference is not a sufficient solution unless the weather signal can be recovered without a significant deterioration of its quality (Fig. 3).

INTERFERENCE IS OBSERVED ALL OVER THE WORLD TODAY. In the United States, the National Weather Service Weather Radar (NEXRAD) network operates in the 2.7–3-GHz

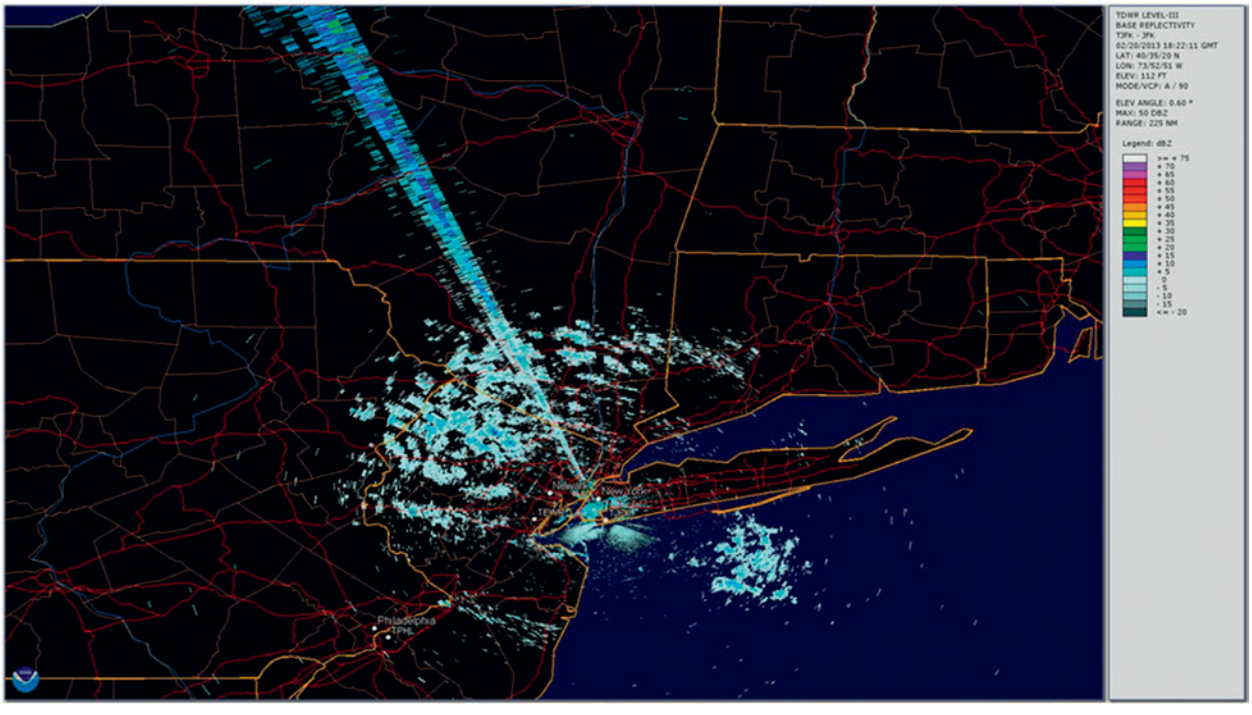

Fig. 1. TDWR radar image from New York (JFK). The signal from north-northwest, which is stronger than any weather signal, is coming from a wireless U-NII device.

portion of the S band. The NEXRAD network of 160 systems is having more and more interference issues. Two major causes of interference to the NEXRAD network are adjacent band interference from wireless networks and in-band interference from other government radars. The most common wireless network interference is from emitters operating in the frequency band just below the NEXRAD frequency. When they operate in the upper end of their band, the out-of-band emissions can cause interference to a NEXRAD operating in the lower end of its band. Another source of adjacent band interference that has been seen in the NEXRAD network is unlicensed wireless devices that have drifted out of specification in association with a hardware failure. On two documented occasions, an unlicensed wireless device

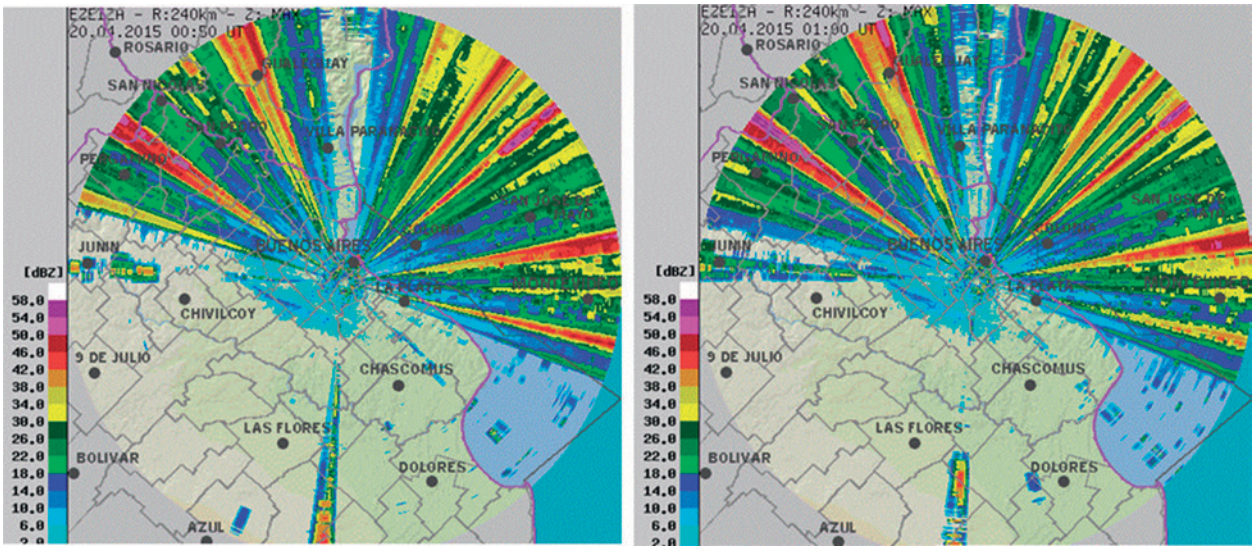

Fig. 2. Images from the Ezeia radar in Argentina, 10 min apart, showing interference at varying intensities. Because the situation changes image to image, the interference cannot be removed by blocking certain radials. Some of the echoes are stronger than the strongest typical weather-related echoes, so filtering of the data for interference would eliminate the identification of hazardous thunderstorms and threaten the safety and security of the public. Images courtesy of Argentinian Weather Service.

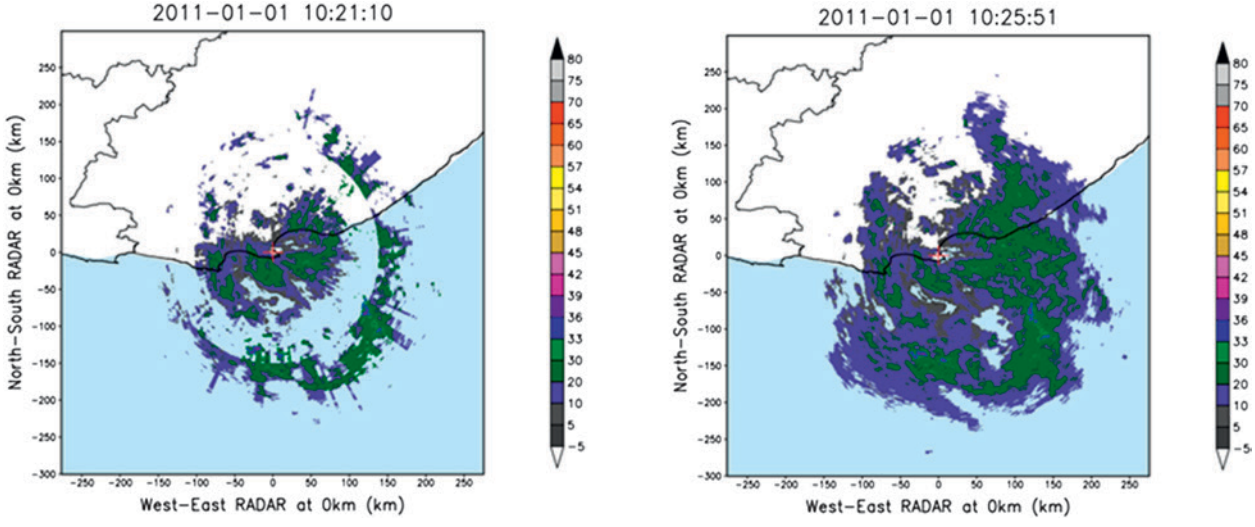

Fig. 3. Port Elizabeth radar in South Africa running (left) with the interference filter and (right) without. The two images are 5 min apart. At this instance no interference was detected during this stratiform rain event, but the active filter still removed a crucial amount of precipitation information. The consequence is that any attempt to accumulate precipitation estimates in the C-band range is severely compromised with significant errors. The RLAN interference effectively renders the precipitation products from the radar useless.

operating at 2.4 GHz has shifted into the NEXRAD band causing interference.

The largest C-band weather radar network in the United States is the Terminal Doppler Weather Radar (TDWR). TDWR is a safety critical system deployed at 45 major U.S. airports by the Federal Aviation Administration (FAA). Its primary mission is detecting weather that is hazardous to aircraft taking off from and landing at terminals, especially microbursts.

TDWR operates in the 5.60–5.65-GHz band. Since 2003, unlicensed national information infrastructure (U-NII) wireless devices were allowed to use the same frequencies, and a majority of TDWR sites have experienced interference from these devices at some point.

As of the date of this publication there has been no known case of a missed wind shear alert due to WD interference. However, the potential certainly exists; therefore, a proactive approach is being utilized by the FAA and Federal Communications Commission (FCC) in eliminating the threats as soon as they are recognized.

In addition to the U-NII devices, there are other devices that have been interfering with TDWRs. Most notable are wireless surveillance cameras with transmitter power higher than allowed for U-NIIs (Tuttle 2012). These devices, while not authorized in the TDWR band, can sometimes be easily tuned to different frequencies by the operator. This is a growing problem as video surveillance is expanding rapidly all over the world.

Mobile platforms such as cruise ships, planes, and trains are an open issue as a source of intermittent interference, as much of the legislation and mitigation techniques apply only for fixed devices. They are a particular challenge for many mitigation schemes, as they come and go at will. Even with stationary units, sometimes as soon as one interference source is tracked down and eliminated another takes its place because a new "vacancy" has been created.

In Europe, the Operational Program for Exchange of Weather Radar Information (OPERA) network consists of 175 C-band radars and 31 S-band radars (Huuskonen et al. 2014; OPERA website (www.eumetnet.eu/opera/), December 2014; Fig. 4). Since 2006, interference to C-band radars from RLAN is increasingly experienced by most OPERA members. In 2014, the Electronic Communications Committee (ECC) has published ECC Report 192, analyzing more than 200 interference cases reported in 2012.

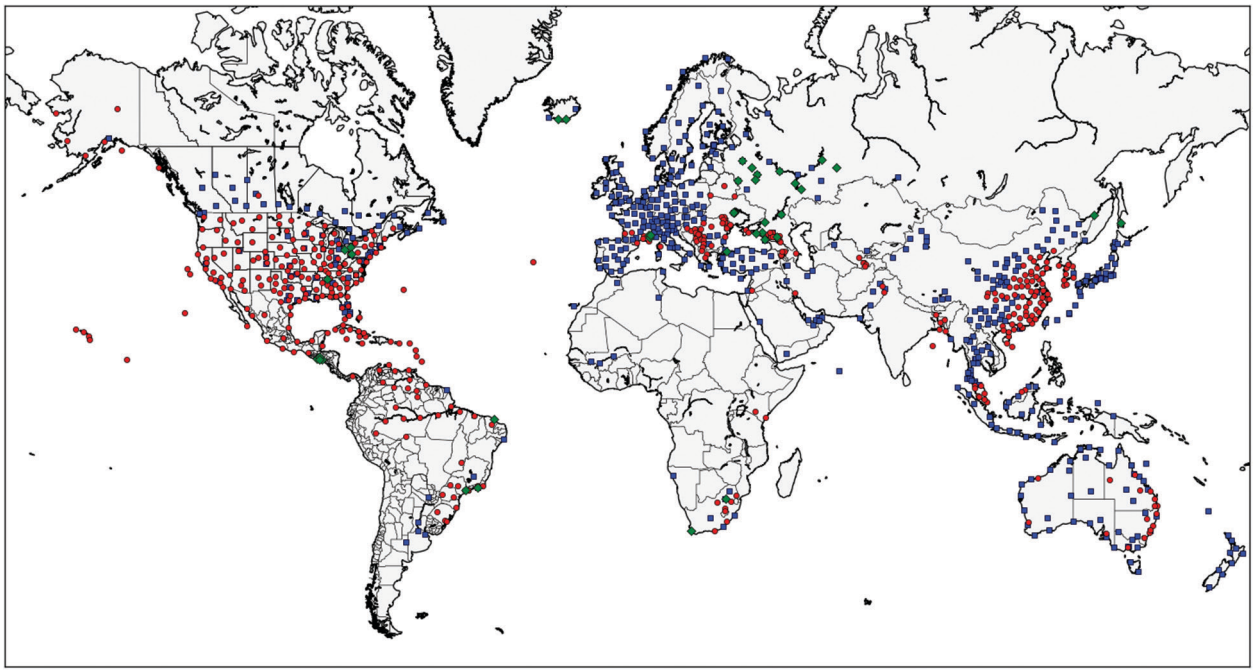

Fig. 4. Distribution of C-, S-, and X-band radars from the current WMO radar database plus additions. It includes 845 radars from 90 countries. There are 454 C bands, 333 S bands, 27 X bands, and 28 S + X combinations. In addition, radar locations from Russia (circa Nov 2013) and China (circa Mar 2004) were deduced from maps available in the open domain and are approximate. There are an additional 38 Russian radars (17 X bands and 21 C bands). There are an additional 87 S-band and 71 C-band radars in China. Both countries are in the midst of significant upgrades to the network. When completed, China will have 123 and 93 S- and C-band radar, respectively.[Sireci 2015; Borisov et al. 2013; NEXRAD Technical Advisory Committee (TAC) 2007].

It confirmed that almost all of the cases were due to intentional illegal use and noncompliant equipment. This report showed that more than 50% of 5-GHz RLAN put on the European market are noncompliant (ECC 2014).

Most South African meteorological radars have experienced interference from noncompliant equipment in the C band, some of them experiencing constant interference. The South African weather services initially tried to implement specific software filtering to improve the situation but then decided in 2011 to move its meteorological radar network to S band.

ATTEMPTS TO SHARE FREQUENCIES AND MITIGATE DISTURBANCES. The use of radio frequencies is controlled globally within the International Telecommunication Union (ITU), which is a specialized agency of the United Nations. It is responsible for the revision of the Radio Regulations, an international treaty governing the use of the radio frequency spectrum, and for regulation of satellite orbits.

At the World Radiocommunication Conference 2003 (WRC-03), the decision was made to provide a primary allocation for the implementation of wireless access systems (WAS), including RLAN, in the bands 5.150–5.350 and 5.470–5.725 GHz, as long as they do not cause interference to incumbent services such as C-band weather radars (ITU Resolution 229; www.itu.int/oth/R0A06000018/en). The two user groups were expected to coexist in the same environment by requiring that WAS/RLANs use a dynamic frequency selection (DFS) function. Before using a channel, the RLAN must check for the presence of radar signals for a time period initially set to 60 s and avoid the frequencies in use by radars. However, more than 10 years after that decision, weather radar operators see more and more interference in the C band.

The variability of the weather radar transmission cycles poses a problem for the effective use of DFS. First, weather radars send very short pulses with length differing between radar systems (0.5–2 μs) to get the necessary range resolution. The pulse repetition frequencies (PRFs) vary as well, even for the same radar. The radar beam is also constantly moving in vertical and horizontal directions, for example, a certain elevation angle is visited variably at every 1–10 min. Hence, it is not always easy for the other devices to notice that a given channel is occupied by a weather radar. Also, in the DFS certification test, a set of waveforms is defined, but it does not necessarily match the waveforms of all the weather radars. Therefore, devices with certified DFS algorithms can miss detecting weather radar signals, for example, from TDWRs (Carroll et al. 2012).

The period during which the DFS needs to monitor a channel before occupying it has been under debate. Already in the 1990s Environment Canada suggested 10 min to match the cycle time of the Canadian weather radar scan strategy employed at the time (J. Scott 1994, personal communication; ITU-R 229, 2003).

Following the initial interference cases in Europe, the DFS specifications in the European Telecommunications Standards Institute (ETSI) Standard EN 301 893 have been modified to impose a 10-min channel availability check (CAC) for RLAN channels covering the 5.60–5.65-GHz band, together with solving other problems that were highlighted such as the minimum pulse width (down to 0.5 μs) and the consideration of the variety of complex weather radar waveforms (fixed, interleaved, or staggered PRF) for which a number of new test signals were added. The organization of European National Meteorological Services (EUMETNET) has also recommended to its members that they include a minimum number of detectable signals in their regular transmission schedule.

The ability of DFS to detect and avoid TDWRs was demonstrated in field tests in a controlled environment with a limited sample of U-NII devices (Carroll et al. 2011). However, investigations by the FAA and National Telecommunications and Information Administration (NTIA) showed that the DFS was either being deliberately disabled by the U-NII operator or was not effectively detecting the TDWR (Pigg 2009; Carroll et al. 2010). Also in Canada and various European countries, there have been instances of interference with devices where the DFS has deliberately been turned off. Locating such devices is not straightforward. While the azimuth of the device is known from the weather radar data, it is not easy to locate the device in range as the ground-based equipment cannot easily replicate the propagation conditions of the weather radar nor perhaps have similar sensitivity or have robust search capability and capacity. This highlights the importance of working with the regulator but also the importance of specifying the terms of spectrum sharing.

Unlike with pulsed radar systems, communication systems such as the U-NII devices have high transmit duty cycles that preclude filtering by single-pulse interference filters like the one implemented in the TDWR (Cho 2011). Furthermore, since the time of the NTIA tests, the TDWR receiver has been upgraded to have higher sensitivity, and in the near future it will be

upgraded to operate in a real-time adaptive multiple PRF mode (Cho and Weber 2010). These changes will necessitate further review of the U-NII interference potential and the DFS certification procedure.

Tests performed in Canada showed that weather radars see the interference as enhanced noise levels resulting in loss of sensitivity. The only way to mitigate the interference would be to implement a variable or adaptable noise filter that would vary from ray to ray. The loss of sensitivity is unacceptable as modern weather radar applications always benefit from increased sensitivity.

Also in tests performed in Canada for the potential use of WLANs in mobile platforms, commercial WDs with DFS mitigation were studied, and the effectiveness of real weather radar detection and channel avoidance algorithm implementations were investigated. WDs detect radars by counting pulses of specific widths at specific repetition rates. It was clear that not all weather radar scan configurations were detected by the radar model proposed. In particular, short pulse (0.5–0.8 μs) and long pulse (2–40 μs) radars may not be detected depending on the algorithm. Several tens of pulses were used to identify the weather radar. The WD was very sensitive, and depending on distance and location, it could detect the weather radar whenever it was operating regardless of azimuth and elevation angle out to a range of at least 40 km (limit of the testing).

Also, when the WD detected a weather radar, it would complete the transmission sequence of packets, and this can take tens/hundreds of milliseconds. All the while, the WD can be creating interference over several degrees of azimuth and elevation.

Given all the considerations, in Canada as well as Australia, the use of 5.60–5.65 GHz has been restricted for use by RLANs (Industry Canada 2007; Australian Communications and Media Authority 2014; Joe et al. 2007). This strategy has worked well for the most part. However, both countries have encountered isolated cases where the notching was not done, was turned off, or the DFS was turned off. The problem cases were resolved after several months of active investigation.

One step in searching for a solution was a request, from the manufacturers and the ITU, to define a weather radar for the purposes of developing algorithms. While an attractive approach, it is fraught with the danger of defining a limiting box in which ever-evolving weather radar technology may be trapped. For example, several manufacturers are now offering solid state pulse compression systems with low power and very long pulses (20–100 μs), but the specifications do not recognize radars with greater than 40-μs pulses (ETSI 2012), and WDs would not detect them. To overcome the blind zone and to achieve the uniform minimum detectable signal, multiple pulses of varying length, with varying transmission time or repetition sequence and with varying frequency, may also be transmitted (Bharadwaj and Chandrasekar 2012). These types of radar are not described nor anticipated in the new definitions (ETSI 2012). WDs could have a much bigger impact on these radars than existing conventional radars due to their low power design. The current technique of DFS with CAC is flawed already and mitigation strategies with these ultrawide band pulse compression radars require detailed analysis and testing. The DFS detection algorithm would have to check multiple channels (varying frequency), assume much more complex variable but cyclic pulsing schemes, and assume different pulse shapes (these radars have range side lobes). The implementation of the DFS scheme to detect a radar is by counting pulses of certain duration and interval. A much more sophisticated algorithm would need to be developed otherwise to minimize the time to detect a radar. Advanced radars with ultrawide bandwidths and an adaptive waveform capability might be able to detect the interference signal from WDs and adjust their operating frequency(s), but this is notional at the moment, unproven, and far from operational implementation. It may even impose greater stress on the spectrum allocation with the possibility of not being able to find a channel(s) to use, especially as WDs are deployed on a massive scale.

The most extreme and expensive reaction to interference in C band was made in South Africa, where the South African Weather Service (SAWS) decided to move its meteorological radar network to the 2.7–2.9-GHz band in 2011. The local authorities first tried to locate and close down the interfering WLANs but could not keep up due to the large number of devices. SAWS also tried to implement specific software filtering to improve the situation. Two factors in filtering the interference have led to the decision to move to S band. First, the resulting interference to the C-band weather radars was severe, and while the filter managed to remove most of the interference, the results were not perfect. Second, the filter also had a tendency to remove weather-related echoes. However, the cost of operating a radar network in the 2.7–2.9-GHz band is expensive and has proven to be a challenge in maintaining a fully operational network 365 days a year.

In Japan, the Ministry of Internal Affairs and Communications is responsible for spectrum allocation. They have sponsored transmitter research on solid state transmitters at C band so that the weather radars will have cleaner spectrum performance where the sidebands and high-order harmonics are reduced. They also plan to segment the C band and halve the bandwidth of the various C-band channels but maintain the same number of channels. They would allocate the lower part of the C band to WDs and the higher part of the C band to weather radar.

Following the Japanese approach globally would pose some practical and regulatory challenges. In some areas such as central Europe, the radars are so close to each other that radar-to-radar interference would be difficult to avoid if only one-half of the band is used. This may be solved by changing the transmitter technology, but the consequences of such a change still need to be studied. In addition, this would require a drastic (and improbable) change in policy in most countries and Europe in particular to impose a notch in the current authorized RLAN/U-NII frequency bands. In any case, as the typical lifetime of a weather radar is 15–20 years, implementing this would take a generation. And finally, as long as the primary problems in Europe are WD transmitters that are illegally operating on radar frequencies, there is no guarantee they would avoid the new, narrower radar band either.

Many modern weather radars, including the NEXRAD, have a mechanical front end interference filter. It is a waveguide filter located between the antenna and the low noise amplifiers. Since the NEXRAD is a dual-polarization radar, there are two of these filters per radar. These filters are primarily to provide a level of selectivity for the broadband LNAs in the NEXRAD system. Without these filters there is a possibility of intermodulation distortion occurring in the LNAs.

One long-term approach that is being considered in the United States is to eventually replace radars performing different missions at different frequency bands (L, C, and S) by one type of multifunction radar at S band using phased array technology (Weber et al. 2007). Such a consolidation of missions could open up the vacated bands (at least partially) for other uses. A similar approach in other regions could be challenging, since it would demand close cooperation over national and institutional borders.

If the image generated by a C-band weather radar is permanently deteriorated in a limited sector (e.g., in the direction of a campus area), an X-band radar could be used there as a gap-filler for precipitation measurements. However, most of the problems that are usually created by one single interferer can suddenly appear in any radar azimuth, and the gap-filler could be implemented only after the problems have been observed. As an extreme solution, and on a theoretical basis, an entire C-band network could be replaced by a dense network of X-band radars such as the proposed Collaborative Adaptive Sensing of the Atmosphere (CASA) radar network (Ruzanski et al. 2011; McLaughlin et al. 2009). However, limited Doppler capabilities in the X band as well as higher

S BAND FOR SEVERE WEATHER, C BAND FOR CONTINENTAL CLIMATE, AND X BAND FOR SPECIAL APPLICATIONS

There are three frequency bands commonly used for weather radars. Lower frequencies have the advantage of the radar signal being able to reach farther due to less attenuation (weakening of radar return signal) by hydrometeors. Radars operating at higher frequencies can employ smaller antennas to achieve the desired angular measurement resolution.

- S-band (2–4 GHz) radars are most commonly deployed in tropical and temperate climate zones, for example, where hurricanes, tornadoes, and monsoon rain are expected or more generally where heavy rains or large hail are common.
- C-band (4–8 GHz) radars are commonly deployed in climates where attenuation by intervening heavy rain or large hail is not such a problem.
- X-band (8–12 GHz) radars are mainly used in shorter-range applications and dense radar networks supporting urban and mountain valley hydrology and on mobile platforms such as airplanes.

The WMO weather radar database (Sireci 2015) has metadata for 845 of the estimated 1500 weather radars in operation around the world by meteorological and other agencies (Fig. 4). Of these, approximately 40% are S-band radars and 53% are C-band radars. The largest S-band network, NEXRAD, is operated by the United States and consists of 160 radars. The network of China, China Next Generation Weather Radar (CINRAD), consists of 158 radars and is a mixture of C-band and S-band radars that have not yet been added to the database.

susceptibility to heavy rains would prevent the use of such a solution as replacement of most current radar networks (e.g., TDWR).

CONCLUSIONS. Interference caused by telecommunication devices is a serious threat to weather radars worldwide. The most efficient protection method is, by joint efforts of the weather community and national and international frequency control authorities, to agree on technological and regulatory methods to keep the disturbing devices out from radar frequencies. This must be an ongoing effort on all levels, and we cannot rest and think "case solved."

There are also technologies to remove the disturbances from radar images at the signal processing or image processing level. Even though they can help with a case of one or a few disturbances, they cannot be considered a permanent and viable solution. WDs are massively deployed on an unlicensed basis, and as the number of interfering devices continues to grow, they will eventually dominate both C and S bands. If we have to retrieve the weather radar signal as a difference of two big numbers (the received signal minus the disturbance), the result cannot be very good and will inevitably affect the use of radar for the public good and downgrade public weather service provision and warnings that save lives and protect infrastructure, property, and businesses.

In this respect, it is now imperative that worldwide weather services as well as radar operators and manufacturers proactively involve themselves in the radio frequency management process and work in close contact with their national radio authorities to ensure that meteorological interests be duly taken into account in any decision-making process toward the future usage of any wireless devices (such as RLAN) within or close to weather radar frequency bands. One easy starting point would be to show this article to the spectrum regulator.

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RLAN, WLAN, WI-FI, OR WD? DFS?

Different terms are used to describe the devices threatening the radar frequencies. Conventional hardwired local area networks (LANs) have evolved to wireless LANs (WLAN) or RLANs to provide wireless resources for a corporate network. Today, a RLAN is also used as a wireless access system to the Internet, from home or office to a broadband Internet connection, or to share an Internet connection for several users in a hotspot (e.g., in a cafe). Those cases are often called Wi-Fi (originally a trademark but commonly used more widely). WAS and WD are more general terms. Wi-Fi generally uses the 2.4- and 5-GHz part of the spectrum (S and C band).

Unlicensed national information infrastructure is another term for Wi-Fi in the C band. Unlicensed means that the devices are approved for use but do not require specific or special application to the spectrum authority to be used. Extra diligence is required before the WD mitigation solutions are approved, as once approved there is no licensing protocol to prevent interference to the weather radar that has primary use of the C band. In this paper, we call these equipment WDs.

DFS is a system in which radio frequencies are monitored and then the WD selects frequencies that are not used by any radars. CAC is part of the DFS scheme where a Wi-Fi channel is monitored for radar signals.

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