EISWG Report on Radar Gaps
6 November 2023

EXECUTIVE SUMMARY

In the 2021 Priorities for Weather Research (PWR) report, a major recommendation was made to immediately start filling gaps in NEXRAD network radar coverage with low-cost radars, while planning for the next post-NEXRAD network. NOAA's 2022 response to the PWR report indicated NOAA would consider coverage as part of its "post-NEXRAD follow-on radar project." Unfortunately, the post-NEXRAD radar generation project implementation is still years away and there are well established solutions that would be highly beneficial in the shorter term.

At the time of this writing, November 2023, NOAA has not prioritized an interim solution. While some radar improvements have been made, the vast majority of radar gaps have not been addressed. Nonetheless, the EISWG Radar Gaps study team recognizes our NOAA colleagues for their commitment to NOAA's mission and vision and understand that there are more demands than resources can address and tough decisions are necessary. We honor and appreciate everything they do for our nation in their roles. Fortunately, the landscape in the area of low-cost gap-filling radars is changing rapidly.

For a small fraction of the likely cost of the envisioned NEXRAD replacement system, which is still many years away, it would be practicable and high impactful to initiate now the purchase and deployment of about 150 gap-filling radars, including installation of 30 within 3 years (per the PWR report recommendation OD-9) to cover underserved and the most vulnerable communities. Alternative solutions should also be explored and primarily include collaborations with private industry as they aggressively pursue a similar solution. Determining the optimal mix or single solution is beyond the scope of this paper.

By moving ahead with more equitable weather services, loss of life and property and economic disruption will be reduced. OD-9 recommended the first phase could deploy 30 radars within three years. ClimaVision, a private sector company, has reportedly deployed about 30 radars within the three years, demonstrating the feasibility of the OD-9 recommendation. There is also the possibility that ClimaVision (and/or similar entity) could be part of the broader solution.

This report recommends that NOAA:

1. **Establish a gap-filling radar data strategy:** Using the EISWG Report (A NESDIS Observing System Backbone Framework) define a radar backbone architecture that will best serve the Nation.
2. **Use commercial data already in hand:** NOAA should act now to more fully leverage currently available commercial radar data, expand it, and use it directly in operations. For any radar data NOAA acquires commercially and uses within NOAA operations, thus incorporating them into the Nation's foundational weather data, NOAA should also acquire the appropriate license to distribute the data on an equal-opportunity basis at

no cost to the end user, in the same format and with the same timeliness as it would have done if the radar data originated from NOAA-owned and operated equipment.

3. **Act immediately to implement the gap-filling radar data strategy:** Using X-band and C-band radars (e.g., commercial data purchases and/or NOAA-deployed backbone), prioritize coverage of, and engagement with, underserved populations.

Purpose

Motivating reasons that EISWG decided to do a report on Radar Gaps, even though the topic was covered and recommendations were made in the PWR report, can be better seen than described – pictures are worth thousands of words.

Figure 1, below, depicts NEXRAD radar coverage superimposed with American Indian tribal lands and U.S. counties color-scaled by Black American census population proportions.

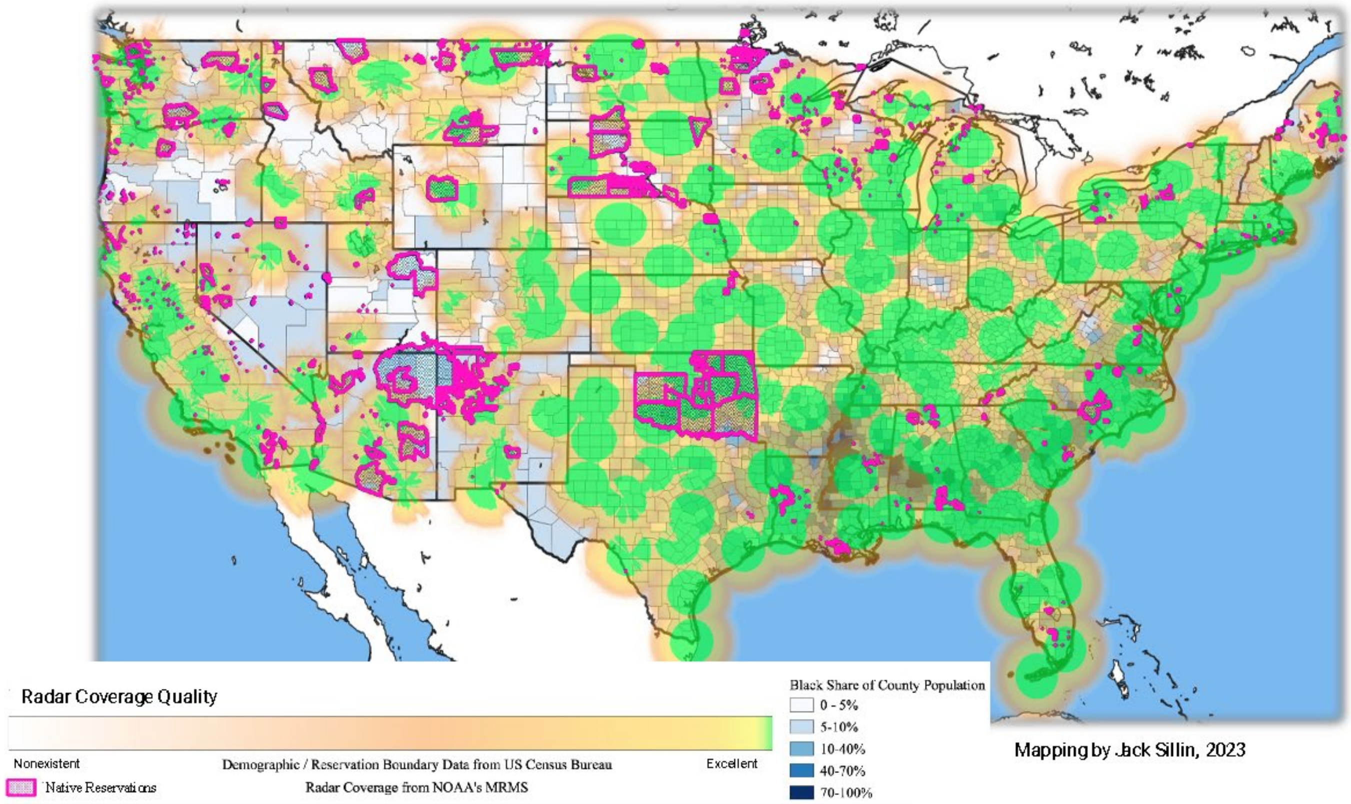

Figure 1. Radar coverage for American Indian Tribal Lands and for Black American-proportionate county populations.

Note that the darker tan and brown colors in the SE US are navy and black (counties with 40%-70% and 70%-100%, respectively, Black American-proportionate census populations) – the radar overlay shifts the hue.

The radar scale has green for NEXRAD at 4000 ft., yellow for NEXRAD at 6000 ft., and brown for NEXRAD coverage at 10,000 ft. Areas between the circles have no coverage.

Figure 2, below, shows the NEXRAD network overlaid by the Center for Disease Control (CDC)/ Agency for Toxic Substances and Disease Registry (ATSDR) Social Vulnerability Index (SVI). Much more than half the uncovered areas contain extremely vulnerable populations.

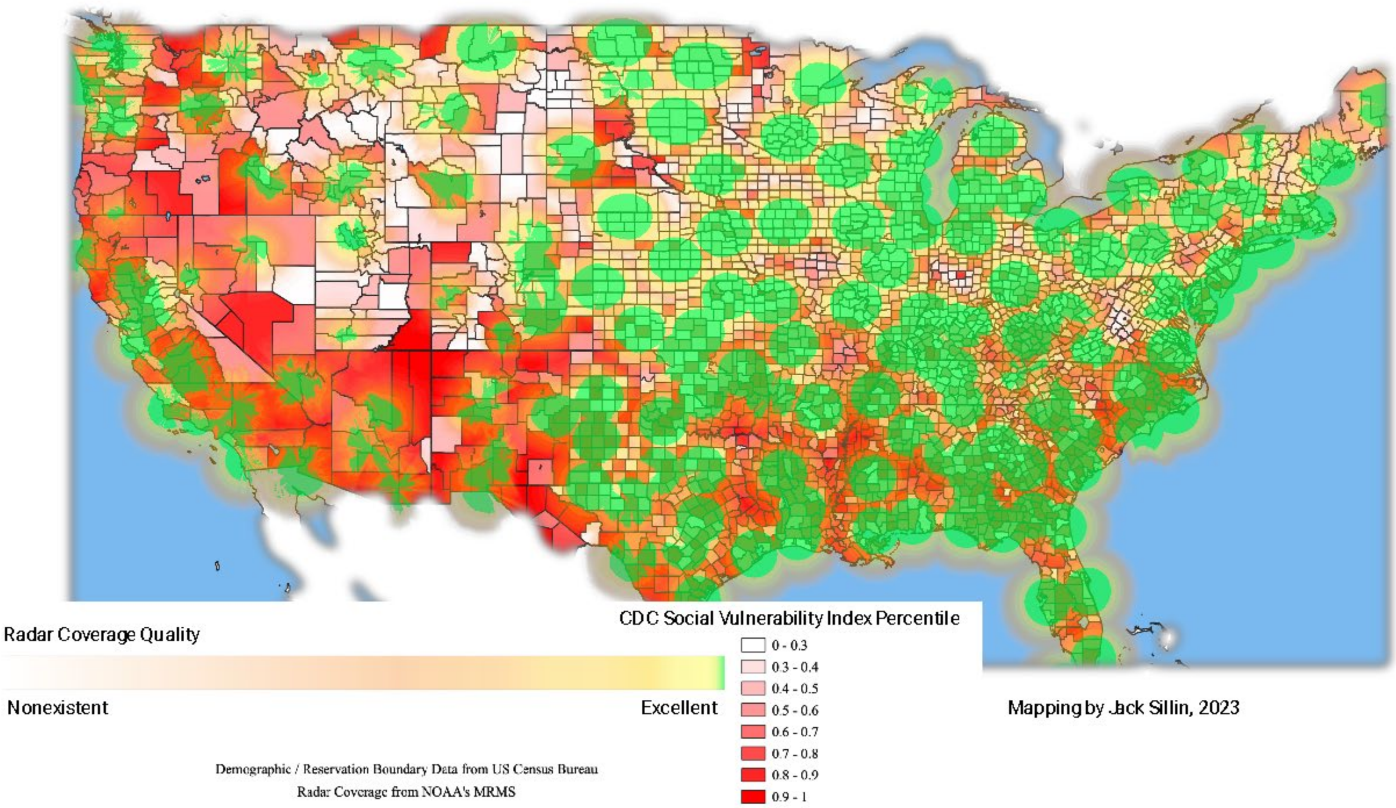

Figure 2. Radar coverage overlaid with SVI.

As in Figure 1, the radar scale has green for NEXRAD at 4000 ft., yellow for NEXRAD at 6000 ft., and brown for NEXRAD coverage at 10,000 ft. Areas between the circles have no coverage.

CDC/ATSDR SVI Themes & Social Factors at a glance:

- Socioeconomic status (below 150% poverty, unemployed, housing cost burden, no high school diploma, no health insurance)
- Household characteristics (aged 65 or older, aged 17 or younger, civilian with a disability, single-parent households, English language proficiency)
- Racial and ethnic minority status (Hispanic or Latino (of any race); Black and African American, Not Hispanic or Latino; American Indian and Alaska Native, Not Hispanic or Latino; Asian, Not Hispanic or Latino; Native Hawaiian and Other Pacific Islander, Not Hispanic or Latino; Two or More Races, Not Hispanic or Latino; Other Races, Not Hispanic or Latino)

- Housing type & transportation (multi-unit structures, mobile homes, crowding, no vehicle, group quarters)[1]

The previous figures are CONUS-only maps that do not depict the coverage gaps in Alaska, Hawaii, or US Territories. In examining radar coverage outside the CONUS, there are also clear opportunities for improvement.

For example, the colored circles in Figure 3, below, depict precipitation data as sensed by Alaska NEXRAD radars over a longer time. The dark blue areas of little or no rainfall during otherwise significant rainfall events stand out as areas with poor quality radar coverage.

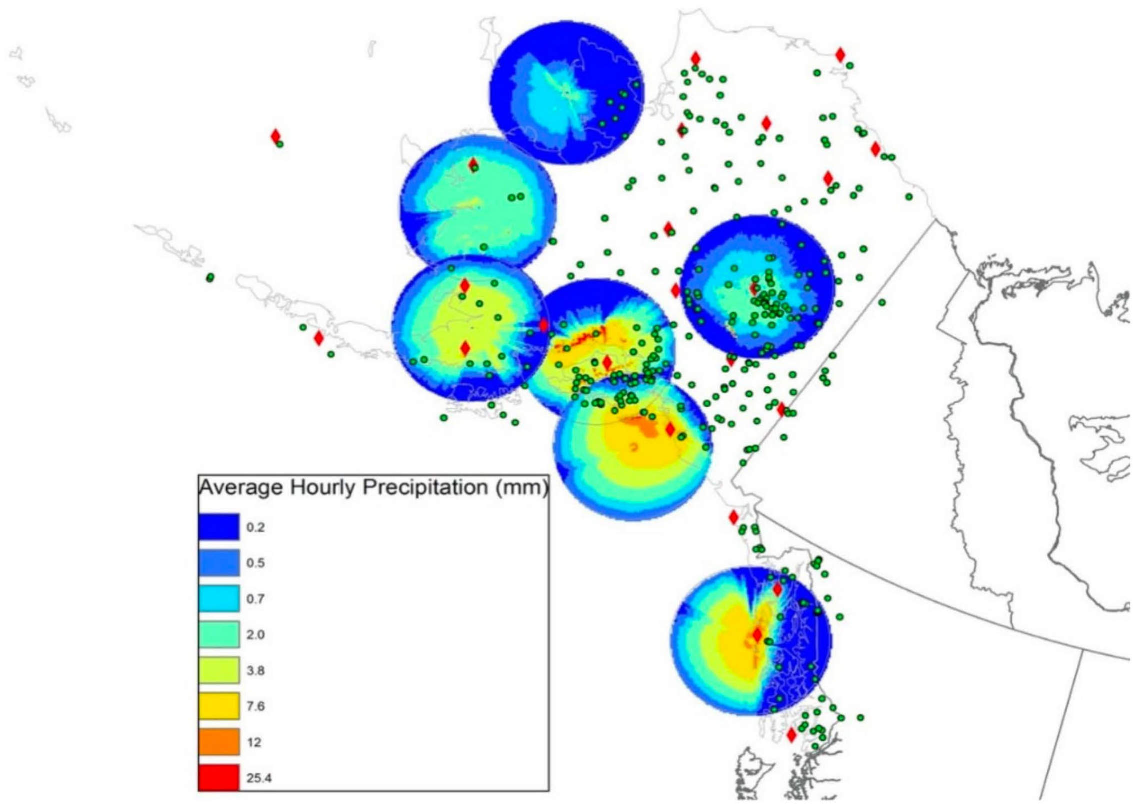

Figure 3. Long-term (2017-2020) average hourly precipitation at each NEXRAD radar site in Alaska (c.f. Nelson et al., 2021).

This figure shows very large areas with no radar coverage, most of them very remote and some presenting serious physical challenges to locate radar infrastructure. Some of these areas, however, also contain indigenous populations.

[1] https://www.atsdr.cdc.gov/placeandhealth/svi/at-a-glance_svi.html

Other Pacific regions are also quite challenged, as shown in Figure 4, below.

Although Hawaii's four NEXRAD radars provide good coverage of Hawaii's populated area, terrain blockage on the north side has a big impact on the ability of forecasters to see precipitation arriving from the north; for these data they rely entirely on rain gauges (personal communication, Warning Coordination Meteorologist, Weather Forecast Office Honolulu).

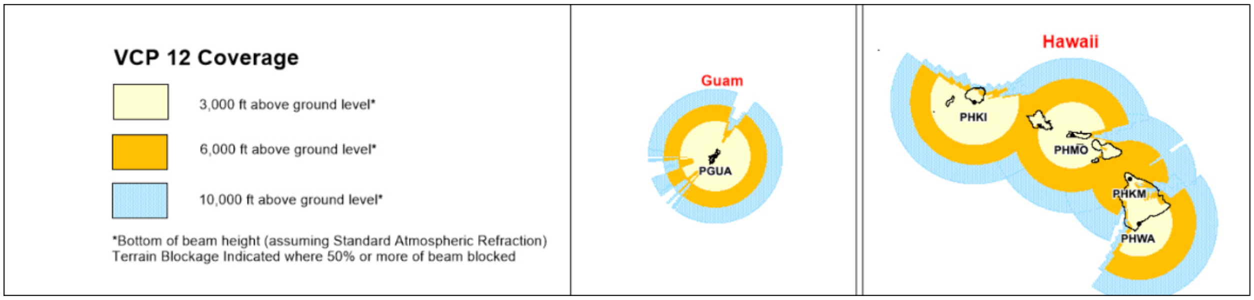

Figure 4. Radar coverage beam height (left), Guam radar coverage (center), Hawaii coverage (right). VCP stands for volume coverage pattern, where VCP-12 is the radar operating in its fastest scanning, default precipitation mode. Puerto Rico VCP-12 coverage is shown on the radar website Contiguous US map: https://www.roc.noaa.gov/WSR88D/Maps.aspx

Guam's (and similarly Puerto Rico's) radar coverage looks excellent, except when one considers that the Guam radar is what is used to create forecast products for radar-less Weather Service Office Pago Pago in American Samoa (personal communication, Warning Coordination Meteorologist, Weather Forecast Office Honolulu). The Guam NEXRAD radar is used to support Pago Pago, about 3,100 nautical miles away from the people it is serving in American Samoa, depicted for approximate scale in Figure 5, below.

Today, radar-derived products from the Guam Weather Service Office are used to support Samoan forecasts out of the NWS WSO Pago Pago.

Figure 5. A Google Earth map showing the distance between Guam and Pago Pago

Background, PWR Report Recommendations History
In the 2021 PWR report, a major recommendation was made to immediately start filling gaps in NEXRAD network radar coverage with low-cost radars:

> OD-9: "Deploy and integrate smaller, cheaper scanning radars into NOAA's current network of very large radars, roughly doubling the number of radars, to better detect significant precipitation and severe weather over more of the Nation and more equitably across the population, starting immediately."

The Findings of the PWR report that drove this recommendation were:

> "1. Currently NOAA ground-based radar observations have a significant limitation in the lower part of the atmosphere due to Earth's curvature and terrain blockage. Seventy percent of the western United States below one kilometer altitude above ground is unobserved and key gaps in coverage in the eastern United States are inordinately where under-represented groups live and work.
>
> 2. Regional networks of small, relatively inexpensive, commercially available radars (C-band and X-band) have seen wide application worldwide and the United States needs to catch up.
>
> 3. The larger, more expensive S-band radars used by NWS as the backbone of national radar coverage are a core capability; remaining gaps can be filled by smaller radars.
>
> 4. Although some regions have the benefit of special radar coverage, primarily through television stations, there are limitations with long-term reliability and equitability of coverage."

Finally, Critical Actions for OD-9 were as follows:

> **"**OD-9.1. NOAA should develop a clear, well-defined process to integrate more fully data from existing radars operated by others to complement NOAA ground-based radars.
>
> OD-9.2. NOAA should begin deploying commercially available, low-cost C-band and X-band radars into areas in the western United States where NEXRAD gaps are most significant, and in the eastern United States where environmental justice analysis has found poor coverage from existing radars, with at least thirty radars deployed within three years."

NOAA's 2022 response to the PWR report included this sentence,

> "NOAA will consider radar coverage as part of post-NEXRAD follow-on radar, considering the benefits and potential impacts on existing capabilities."

The big-iron NEXRAD radar replacement is an extremely important project that will require scientific analysis and, potentially, technological development. When completed it will create a robust, resilient backbone of coverage for the nation well into the future, but for which implementation is years away.

NOAA's response also correctly notes that the Multi-radar Multi-sensor (MRMS) Quantitative Precipitation Estimation system (QPE), which includes multiple radars, satellites, and rain gauge data, is being used to help fill radar gaps. However, it is well known that serious limitations remain in representing precipitation rates in real time in this way. Also, detection of severe weather conditions involving winds are a key role for gap-filling radars that are not part of QPE. The gaps in MRMS and satellite precipitation estimates are exactly where the gap-filling radars are well-suited to fill with high precision and quality, thereby helping to address the weather forecast and warning needs of some of the most vulnerable and underrepresented groups in the nation.

While NOAA has not made the progress envisioned in implementing the PWR OD-9 Recommendation, incremental improvements to existing radars have been made – some planning, changes in NEXRAD beam angles, inclusion of Terminal Doppler Weather Radar (TDWR, used by air traffic control for wind shear warnings) data. NOAA is also engaged in the pilot purchase of private sector-supplied radar data, which has installed 26 new radars at the time of this report, primarily in the southeast U.S.

Fundamentally, however, radar gaps are not yet being addressed and the need is urgent.

How Urgency and Backbone Relate
"Urgency" refers to what is needed today. "Backbone" architecture refers to the careful planning to design a robust, resilient solution that will serve NOAA well into the future.

The National Weather Service (NWS) Director has identified future radar solutions as a top-10 priority. Americans are at risk *now* due to gaps in, or poor, radar coverage *especially* in traditionally underserved communities and where terrain limits the usefulness of NEXRAD. The immediate need for expanded radar coverage is urgent, especially with increasingly frequent and extreme weather, drought, rainfall, and floods. Snow squalls also present a hazard that particularly impacts highway safety and can be detected with good radar coverage. Many stretches of interstate carrying U.S. commerce are not covered by the radar network required to provide early warnings to drivers.

Regardless of the technology eventually selected to replace the original NEXRAD system, the siting of those radars is still constrained by the landscape itself; our majestic mountains, valleys, and grand scale. It is likely NOAA's future radar network will comprise a core group of NEXRAD-successor radars – maybe a new solid-state technology, maybe the existing network upgraded once again with good coverage over longer ranges – hybridized with shorter-range, more numerous radars that offer higher spatial and/or temporal resolution. Designing and deploying this system has its own urgency as the existing NEXRAD network is aging and there are no replacement radars today.

In addition to the PWR report, previous analytic studies have identified and described the need and benefit of gap-filling radars (e.g., Chandrasekar et al., 2018; Cifelli et al., 2023; Biswas et al., 2022). The required technology is available (X-band and C-band radars can be acquired “off the shelf”); no major technical barriers exist. A peer-reviewed technical paper on X-band gap-filling radar demonstration from several years ago (Chandrasekar et al., 2018) describes the network and illustrates its applications to severe weather monitoring and predictions. The main benefits of the gap-filling radar for a densely populated area are the greater spatial and temporal resolution of the radar data, and filling the altitude-based measurement gap.

This urgency has already powered the private sector and the academic sectors to make progress. Since the PWR report, at least 30 private-sector X-band radars have been deployed in eastern and southern areas of the US that are underserved by NEXRAD. In Texas and on the west coast, state and/or regional entities have funded C- and X-band radars that ameliorate the inadequate NEXRAD coverage for Dallas-Fort Worth areas (Chandrasekar et al., 2018) and for the San Francisco Bay region (Cifelli et al., 2023, Biswas et al., 2022).

It should be noted that NOAA’s mission includes not only collecting observations but also reliably and quickly distributing the data (see, for example, NOAA’s Environmental Data Partnership Agreement). This should include any radar data that NOAA acquires as a gap-filling component to supplement deficiencies in the NEXRAD network. This is an important issue because the entire Weather Enterprise, including emergency managers, broadcast meteorologists, weather media, America's Weather Industry, and many industry segments, all rely on these foundational data. The Weather Enterprise works with NOAA to substantially enhance, extend, and multiply the value of foundational data, model outputs and warnings thus contributing to the protection of lives and property and sharing responsibility for reducing the negative impact of weather on the economy.

Study Process and Approach

The Radar Gaps study team interviewed representatives from NOAA, academic programs, and commercial data providers. Findings and Recommendations reflect common themes from these interviews.

CURRENT FINDINGS

This report’s findings describe

- how the current NEXRAD radar coverage creates additional vulnerability for underrepresented populations,
- how gap-filling radars differ from NEXRAD radars,
- the origins of radar gaps,
- how gap-filling radars help, and
- how this presents an opportunity for NOAA to help fulfill its responsibility to protect public safety.

Observational requirements drove the original technical solution to S-band and terrain was a factor in siting decisions. For example, coverage, beam forming/side lobes management, and multi-agency needs were among the siting decision criteria. In mountainous regions, additional expense was experienced because siting was required in remote locations. These remote locations also ensured the requirements for the National Airspace System (NAS, for FAA-controlled enroute airspace 10,000 feet and above) were met.

However, although covering populated areas was a primary goal, there are nevertheless regions containing populations that are not adequately covered by the original NEXRAD siting. Postponing investment by NOAA that would equitably ensure vital and reliable radar coverage for the nation, including for underrepresented groups, is putting American lives and livelihoods at risk.

> FINDING 1: Indian Reservations and other populations remain underserved. Today, many citizens are at risk due to no (or inadequate) radar coverage, in multiple areas of the country. Areas of the U.S. that were neglected or on the margin due to feasibility when NEXRAD was laid out in the 1980/90s can and should be better protected today.
>
> - Many areas are now feasible to protect due to new technology, but populations are not yet adequately protected because the existing system hasn't been changed.
> - Rural areas have experienced increased development, resulting in heightened environmental risk. A recent report shows urban populations are expanding into, rather than away from, flood-risk zones, even as overall flood risk is increasing (Rentschler et al., 2023).

As specific examples, the lack of NEXRAD coverage is especially true at many American Indian tribal lands and for areas with proportionately higher Black American population counties (see radar coverage overlay on tribal lands and county-proportionate Black American census numbers in Figure 1).

An even more powerful picture is painted using the CDC/ATSDR Social Vulnerability Index (CDC/ATSDR SVI) [2], a 16-census-variables index developed to help FEMA and local officials identify communities that may need support before, during, or after disasters (see radar coverage overlaid with this index in Figure 2).

The next section describes the manner in which gap-filling radars benefit NOAA's mission.

> FINDING 2: How gap-filling radars differ from NEXRAD radars. The higher the radar's radio frequency, the shorter the useful range, the greater the spatial resolution of the data, the greater the degree to which the sensing signal itself is blocked by rainfall (aka

[2] https://www.atsdr.cdc.gov/placeandhealth/svi/index.html

rain fade), the smaller the antenna size and energy used, and generally lower cost. The S-, C-, and X- spectral bands refer to the increases in frequency used by the radars.

(a) NEXRAD's "big-iron" S-band radars are relatively high-power and, due to the spectral band they use for sensing (lower frequency than the gap-filling radars), can collect rainfall data with good accuracy (especially the modernized dual-polarized radars) over larger areas than an individual X- or C-band during more intense rainfall events. However, at far enough range, these radars' performance has serious errors due to the radar beam becoming too high above the ground (e.g., Matrosov et al., 2014).
(b) C-band radars, higher in frequency, but less expensive than the S-band, still perform over relatively larger areas and can fill in NEXRAD gaps at lower cost per area covered.
(c) X-band radars are the highest in frequency of weather radars, are less powerful, are still less expensive, have a more limited range (~60 miles), and can be less useful for quantifying extremely intense areal rainfall due to loss of radar signal in the heaviest rain. Attenuation can also be caused by hail and wet snow or ice during winter weather. X-band radars have the highest spatial resolution and they thus "see" a great amount of detail, making them incredibly useful for understanding weather event storm structures, including signatures of tornadoes, and of narrow cold frontal rainbands (that can create severe urban and small stream flooding, shut roadways, and cause often deadly post-wildfire debris flows).

Today, all these radar types are available from multiple providers.

FINDING 3: Origins of radar gaps. The gaps in radar coverage are fundamentally physical in their origins:

(a) mountains block radar sampling, so siting the few big-iron radars in valleys seriously reduces areal coverage, and
(b) siting radars on mountains worsens the problem of the radar beam rather quickly becoming too high above the ground to see the vital lowest 5,000 feet (above ground level; AGL) of storm structure and precipitation signals… because the curvature of the earth bends downward too quickly (radars overshoot the weather at increasing distance from the radar).
(c) The original NEXRAD network required S-band radars as the then-best-technology, so the resulting architecture was considered the best possible. However, there are long distances between some of the radars in that network, producing zero coverage of some areas, particularly in the west.

Since the original WSR-88 S-Band deployment ("88" because it was intended for deployment in 1988, but didn't get out there until about 1993), radar data have been enriched with dual-polarized technology and the existing network updated, thus producing better (but still error-prone at long ranges) rainfall estimates, and *without improvement in spatial coverage*.

FINDING 4: How gap-filling radars help. “Small-iron” X-band and C-band radars are a fraction of the cost of the big-iron systems. They can be placed in many more locations, which allows valleys and the lowest 5000 feet above ground level (AGL) to be sampled far more completely, providing more accurate precipitation estimates and thus flash flood warnings, as well as storm structures informing severe weather warnings for tornadoes and other high-wind events.

One very big change in recent decades was the technology innovation (e.g., through NSF’s “CASA” program) and commercialization of less expensive technology that operates in the higher frequency X and C spectral bands. This reduces some capability relative to S-band devices, but the units are much, much less expensive (on the order of 90% less).

As a result, lower-cost solutions using off-the-shelf technology have been in use over the last 20+ years. Numerous examples exist of these radars being used to fill coverage gaps or provide data for lower levels than available NEXRAD beam heights. These solutions have been adopted by national meteorological services in vulnerable regions of the world with less economic power than the U.S. In addition, enterprising communities in the U.S. have invested in their own X-band and C-band radars to address specific areas of concern, protecting areas that have poor NEXRAD coverage and high severe weather and/or flash flood or urban and small stream flooding potential (e.g., Chandrasekar et al., 2018).

These alternative approaches cost much less per unit than a one-size-fits-all "big-iron" large radar solution. Today, the tradeoffs among the radar types can be combined and hybridized to optimize their combined application. This is analogous to NOAA’s approach to the High Frequency (HF) Radars in the NOAA ocean surface current mapping network. The national network uses different brands and frequencies of HF Radars. Different frequencies produce different ranges and resolutions, which are tuned to local needs. Data flow to operational forecast centers is coordinated through one national Data Aggregation Center (DAC). They are all needed to fill the profound gaps that inevitably remain without them.

Commercial Resources

The private sector has long offered lower-cost weather radars. There was a time 15-20 years ago when every big city TV meteorologist was motivated to have their own radar and their broadcast TV stations attempted to leverage the individual radars for marketing. Over time, having a radar became less differentiating, and, as both NOAA and commercial forecasts improved, the assumption that TV stations would buy, adequately maintain radars, and share their data appropriately, proved unjustified in many cases. Looking back, even in economically prosperous areas with poor NEXRAD coverage (e.g., the San Francisco Bay area) this approach never succeeded in filling the gaps.

Nevertheless, the private sector is growingly an important partner resource to NOAA. As climate change is pushing both awareness and cost in the private sector, there is growth in business opportunities to invest profitably in both sensing platforms and data analytics.

Companies bring technology innovations, are usually faster to deploy projects, and do not rely on US national political processes to fund their efforts.

Today there are at least two new companies planning to fill some radar gaps in the U.S. using their private investment muscle. They are launching new/experimental satellite-borne radars and deploying ground-based X-band and C-band radars. By selling their data and analytics to entities with specific weather-dependent needs (e.g., energy market, agriculture, transportation), their business plan is to help manage escalating weather and climate risk adaptation. They are also working to provide data to NOAA.

- One company is reportedly on track to have deployed their initial 30 radars in 3 years, which is the same time frame recommended in the PWR report, thus demonstrating the practicability of the recommended time frame. Data from the radars are being provided to NOAA and reportedly integrated with operational products. However, whereas some areas of poorer NEXRAD coverage will be helped, it is clear that a NOAA backbone is still needed especially for areas of disadvantaged communities, as this coverage by itself is not the sole criterion for radar site selection by the company.

  FINDING 5: Integration of commercial data can help. Where commercial providers are ready to sell radar data to NOAA and NOAA is already engaged with them in various pilot projects, NOAA can use this opportunity to integrate unique data into the existing radar products, especially in areas where there are gaps. Commercial providers have been gaining experience in the US and elsewhere with small-iron radars and can be useful partners to NOAA in helping design NOAA's post-NEXRAD radar backbone architecture.

  FINDING 6: Purely commercial radar rollouts will leave some populations uncovered. The full rollout of private ground-based radars will likely fill some gaps and will enhance some areas with weaker NEXRAD coverage, but the impetus to place radars in areas of poor coverage nevertheless requires economic interests nearby to fund their operation.

It may be that NOAA can leverage existing and future commercial implementations by contracting long-term with their providers for data. NOAA may also contract with willing companies to deploy radars in locations that might otherwise be undesirable from a commercial business perspective. In either case, however, in order for these to reliably fill gaps, NOAA must create a data stream reliable in its timeliness, quality and duration, by making a program that is resilient in the face of government budget challenges and/or the vagaries of a yet-to-be-time-tested private sector business model.

Academic Partners

Research represents a vital component of an effective gap-filling radar program. It ensures the solutions are not stagnant over time and that new methods, tools, diagnostics, decision support systems can be developed and tested. This extends to having responsibilities for development and leadership of multi-year pilot studies and demonstrations in partnership with NWS and the private sector.

Another key role for the academic sector is in education and training to ensure the highly technical workforce is available to meet what is required for gap-filling radar systems to be most effective. Finally, universities provide a form of neutral ground that fosters not only technical solutions that are creative, but also nimble organizational approaches to suit the needs of a regionally optimized system.

As an example, the Advanced Quantitative Precipitation Information (AQPI) program[3], sponsored largely by the State of California, has created a network in the San Francisco Bay area. Phase 1, the creation of the network, is nearly complete, and Phase 2, the "Demonstrate and Enhance" phase, is being led by a university-based research center that develops and demonstrates prototype observing, modeling and decision support systems. Its results have helped inform what is possible using such radars in mountainous urban terrain.

Creating a Federal Radar Backbone

It's clear that NOAA needs a backbone architecture that will serve its requirements both now and into the future. It's also clear that NOAA will need to look at approaches that differ from its previous model for a one-size-fits-all network, as technology has progressed and deploying a hybrid network is most likely to better fill its future needs.

Another EISWG report has been prepared in parallel with this one: **EISWG Report on A NESDIS Observing System Backbone Framework**. That report uses Radio Occultation data as the observation data type to create this framework. There is some shared authorship across the two reports, and both reports were reviewed by the full EISWG prior to submission to the SAB.

The study team for this Radar Gaps report and the EISWG as a whole agree that the framework for NOAA's backbone approach to their requirements for environmental observations can and should be applied to NOAA's next-generation radar system development. An excerpt from the report outlining the general approach can be found in Appendix 2.

> FINDING 7: NOAA can work with private and academic sectors on the backbone. A next-generation national backbone system will likely include modern big-iron radars plus many small-iron radars tailored to fill key gaps in the big-iron. Such a network is technologically feasible and cost effective. NOAA will benefit from full engagement with partners to complete the plan.

Federal Responsibility

While working with commercial partners will be immensely useful to NOAA and could help taxpayers save money and time, in doing so NOAA should make sure it has the budget and the

[3] https://psl.noaa.gov/aqpi/, https://cw3e.ucsd.edu/aqpi/: These two sites provide a good introduction to the AQPI program.

contractual stability required so citizens can safely rely on NOAA to help them protect their lives and property.

Where those different missions are aligned, commercial-NOAA partnerships will be beneficial to all, but the basic responsibility to create a robust and reliable backbone radar network lies with NOAA.

NOAA's commitment to fulfilling its responsibility is clear:

> "The Biden-Harris Administration's Budget for Fiscal Year (FY) 2024 demonstrates strong support for NOAA's *goal of building a climate-ready nation where communities, individuals and industries have the authoritative and actionable information they need to address climate impacts*," said NOAA Administrator Rick Spinrad, Ph.D. "The FY 2024 Budget will allow NOAA to continue *enhancing all aspects of our science and service delivery — from strengthening our observational infrastructure to working with vulnerable communities on resilience planning* — while supporting sustainable economic growth through innovation and collaboration."[4] (*emphasis added*)

The environmental risks that radar coverage is vital to managing and mitigating are on the increase. Extreme weather and rainfall events happen more often and in more locations.[5]

NOAA has updated its policy on Tribal consultation (NAO 218-8A)[6], and it also has the opportunity to expand on its forecast coverage and engagement with Federally Recognized Indian Tribal Governments.

Using Indian Reservations as an example, NOAA could engage in the following ways:

- First, engage immediately with tribal leaders to cover the neediest areas first.
- Fill the gaps: Add radars to ensure adequate coverage for forecast needs. WFOs could engage tribal members on the upcoming radar and/or weather station installations, for example, fulfilling ongoing operation and deployment maintenance related tasks either under contract or as internships under ongoing STEM activity.
- The Warning Coordination Meteorologist (WCM) or other appropriate resource at every WFO with tribal reservations in their forecast purview could meet regularly with Tribal leadership and their Emergency Management team to deepen or establish a relationship of trust and to learn about the specific forecast and warning needs of the tribal community.
- NWS could convene an "insight committee" consisting of tribal representation from many different American Indian tribal locations to provide insight and feedback on weather information and warnings to improve NWS support to Tribes as sovereign nations.

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[4] NOAA's FY 2024 budget: Building a climate-ready nation

[5] Extreme weather and climate change: an IPCC special report (2023)

[6] NOAA NAO 218-8A

This approach, modified for other areas and situations, may serve NOAA well in engaging with other underserved populations.

RECOMMENDATIONS

RECOMMENDATION 1. Establish a gap-filling radar data framework strategy: Using the EISWG Report (A NESDIS Observing System Backbone Framework) define a radar backbone architecture that will best serve the Nation.

Full engagement with the weather Community, which already has gap-filling radar experience, will minimize time to deployment and optimize the strengths of all components by employing best practices. The extra-NOAA weather domain is positioned to help NOAA both to fill its gaps, as long as NOAA has the budgetary and contractual strength to assure ongoing success, and to assist NOAA in the design of its next-generation radar network.

The following steps are suggested as a model for how NOAA could move forward quickly:

Step 1: A panel of NOAA and non-NOAA experts is formed/tasked to create a SMART[7] roadmap to deploy the network of gap-filling radars recommended.

Step 2: In concert with the gap-filling plan, NOAA leverages the panel's expertise to inform the nature of its next-generation radar network. Wherever possible, the initial gap-filling radars should support the future as well as the current network.

Step 3: NOAA covers the costs for the panel to do its work, thus promoting swift action and diverse participation.

A key to success for any project relying on team effort is the co-creation of a scoping document with cross-team leadership. Buy-in on the scope by the people producing the plan, the people approving the plan, and the people accepting the plan, is critical. From that early scoping document, the team can effectively move on to implementation, that includes who is involved, meeting schedules, and frequent check-ins with other team leaders along the way. For example, the PWR report was developed in this way, co-designed with EISWG, SAB and NOAA leadership.

So, for example, the Filling Radar Gaps implementation could look like this:

Form panel of experts, including NOAA and external radar experts and stakeholders (incl. tribal). Key technical, programmatic and policy experts will step up; Community is eager for decisive action.

- Charge/empower the panel to develop a roadmap and implementation plan, including Operations and Maintenance costs, that also take into account each of the PWR Report recommendations.
- Define key elements: Federal backbone, and hybrid Community participation.
- Create key performance indicators and milestone-based timeline to assess progress and make them available to the panel to foster transparency.

[7] Specific Measurable Achievable Realistic Time-limited (SMART)

NOAA should develop a comprehensive implementation plan, in consultation with the expert panel, including a necessary budget request. The Community can help communicate and provide outreach on the importance of this work.

RECOMMENDATION 2. Use commercial data already in hand: NOAA should act now to more fully leverage currently available commercial radar data, expand it, and use it directly in operations. For any radar data NOAA acquires commercially and uses within NOAA operations, thus incorporating them into the country's foundational weather data, NOAA should also acquire the appropriate license to distribute the data on an equal-opportunity basis at no cost to the end user, in the same format and with the same timeliness as it would have done if the radar data originated from NOAA-owned and operated equipment.

RECOMMENDATION 3. Act immediately to implement a gap-filling radar strategy: Using X-band and C-band radars (e.g., commercial data purchases and/or NOAA-deployed backbone), prioritize coverage of, and engagement with, underserved populations**.**

SUMMARY AND CLOSING

The Nation's need for gap-filling radars has not diminished in the two years since the 2021 PWR Report recommendations. Now is the time for NOAA to initiate the actions required. Without it, people in especially vulnerable communities will continue to face extreme weather and water impacts with lesser quality and amount of information that could help protect their safety, communities, and economies.

The EISWG Radar Gaps study team understands many of the challenges faced by federal agencies and staff who are dedicated to providing life-saving, economical and societally beneficial data, and services. NOAA, its staff, partners, and suppliers provide an incredibly important foundation for the vibrant weather-water-climate enterprise (public, private and academic) that our nation depends upon day in and day out. This report is aimed at helping close key gaps that have remained over time, and are now reachable through modern technology and partnerships… in an era where infrastructure investments are being made to help our nation weather the changes in weather and water extremes and vulnerabilities that are causing increasing disruption, including rapid increases in billion-dollar natural disasters.

It is EISWG's role here to make recommendations where we as non-NOAA domain experts see that NOAA has an opportunity to improve the outcomes of their dedication and work. It has been an honor for us to work on this report. EISWG welcomes the opportunity to continue working with NOAA to address the growing needs of a Weather Ready Nation.

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APPENDICES

APPENDIX 1a. Summary of Radar Gap-filling Recommendations with excerpts from Priorities for Weather Research (PWR; NOAA/SAB 2021)

The consensus of the PWR Study Team was that there was urgent need to immediately expand U.S. investments in weather research and forecasting across the entire value chain, and to dramatically increase that upward trend over the next decade.

The Report highlighted immediate first steps across four core areas, one of those being Infrastructure, including an "immediate first step:" "Fill gaps in existing Earth system observing networks with existing, proven or augmenting technologies to expand coverage, especially in underserved regions."

In the main body of the Report, Observations and Data Assimilation (OD) was called out as the first of three pillars in the overall report framework – the framework that illustrates the foundational elements and process of NOAA's development and delivery of weather information.

The "OD-9" Recommendation focused specifically on gap-filling radar:

> OD-9: "Deploy and integrate smaller, cheaper scanning radars into NOAA's current network of very large radars, roughly doubling the number of radars, to better detect significant precipitation and severe weather over more of the Nation and more equitably across the population, starting immediately.

The Findings of the report that drove this recommendation were:

"1. Currently NOAA ground-based radar observations have a significant limitation in the lower part of the atmosphere due to Earth's curvature and terrain blockage. Seventy percent of the western United States below one kilometer altitude above ground is unobserved and key gaps in coverage in the eastern United States are inordinately where under-represented groups live and work.

2. Regional networks of small, relatively inexpensive, commercially available radars (C-band and X-band) have seen wide application worldwide and the United States needs to catch up.

3. The larger, more expensive S-band radars used by NWS as the backbone of national radar coverage are a core capability; remaining gaps can be filled by smaller radars.

4. Although some regions have the benefit of special radar coverage, primarily through television stations, there are limitations with long-term reliability and equitability of coverage."

The Critical Actions associated with the OD-9 recommendations were:

> **OD-9.1.** NOAA should develop a clear, well-defined process to integrate more fully data from existing radars operated by others to complement NOAA ground-based radars.
>
> **OD-9.2**. NOAA should begin deploying commercially available, low-cost C-band and X-band radars into areas in the western United States where NEXRAD gaps are most significant, and in the eastern United States where environmental justice analysis has found poor coverage from existing radars, with at least thirty radars deployed within three years."

APPENDIX 1b. Excerpt from NOAA's response to PWR report.

In late 2022, NOAA provided to NOAA SAB a written response to the PWR Report https://sab.noaa.gov/wp-content/uploads/NOAA-Response-to-SAB-PWR-Report_28Nov22_Final.pdf

Recommendation OD-9; Critical Actions OD-9.1, 9.2 Recommendation: Fill radar gaps using diverse weather radars and data assimilation. Deploy and integrate smaller, cheaper scanning radars into NOAA's current network of very large radars, roughly doubling the number of radars, to better detect significant precipitation and severe weather over more of the Nation and more equitably across the population, starting immediately.

(NOAA) Response: The NOAA Strategic Plan underscores advancing critical research on weather radar technologies and operations to meet the unprecedented challenges of weather observing and forecasting in the coming decades. The NWS continually updates its policy for the use of non-NOAA radar data; NOAA currently has ongoing research efforts to analyze the potential benefits that data from supplemental radars could add to numerical models. Presently, non-radar observational platforms and advanced data integration applications are being used to supplement radar coverage. For example, there are collaborative efforts between NOAA and its partners to create Quantitative Precipitation Estimates (QPE) from satellite observations over rough terrain, which is typically not observable with traditional radar systems. The Multi-Radar Multi-Sensor (MRMS) is a system that integrates data from a variety of sources including radar, surface and upper air observations, lightning detection systems, satellite observations, and forecast models to produce QPE and other products for use in meteorological and hydrological forecasting. The MRMS ingests WSR-88D and Canadian radar networks, along with one state-owned, commercial radar. MRMS advancements also include surface precipitation estimates with evaporation corrections and radar data overlapping techniques. NOAA will consider radar coverage as part of post-NEXRAD follow-on radar, considering the benefits and potential impacts on existing capabilities. (color added)

APPENDIX 2. Excerpt from EISWG Report on A NESDIS Observing System Backbone Framework

This excerpt is provided to show the general approach taken for defining the framework to creating a backbone architecture for NOAA observational data.

".... the study team determined that a comprehensive approach could be based on a framework structured around the following three guidelines:

1. *GUIDELINE 1: Employ a Data-Oriented, End-Use Approach.* Start from a data perspective, optimizing overall data sets (multiple sources) for end-use performance/effectiveness, cost, and risk (for the purpose of this report, end-use primarily refers to uses by operational forecasting centers or NOAA data centers).
2. *GUIDELINE 2: Focus on an "Enabling" Backbone.* Define and implement backbone Observational Data Element (ODE) with characteristics that enable the best overall ODE, which may reflect some combination of backbone data and alternative-source data.
3. *GUIDELINE 3: Actively Assess and Nurture Alternatives.* Actively nurture commercial markets or other sources to ensure growing and increasingly robust alternative data sources." ....