NOAA SCIENCE ADVISORY BOARD REPORT ON A NESDIS OBSERVING SYSTEM BACKBONE FRAMEWORK

PRESENTED TO THE NOAA SCIENCE ADVISORY BOARD
BY THE ENVIRONMENTAL INFORMATION SERVICES WORKING GROUP (EISWG)

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A NESDIS Observing System Backbone Framework

Purpose, Motivation, and Background

NOAA's recent effort to explore commercial satellite data as alternative sources to data from dedicated NOAA satellites has raised important questions. Can these data replace all or portions of NOAA data? Can that be done at a lower cost, with acceptable performance and risk? Under what circumstances should NOAA maintain its own "backbone" systems even when acceptable commercial sources for those data are available, and what characteristics should those backbone systems have? This report provides a framework for answering those questions. It focuses on the NOAA's NESDIS spaceborne observing capability but includes a discussion of generalizing the approach to other NOAA observing systems.

A concrete example of these issues has arisen with NOAA's need for radio occultation (RO) data. RO data provide accurate and timely measurements of temperature, humidity, and pressure throughout the atmosphere. Used in the initialization process of numerical weather prediction (NWP) models which generate weather forecasts, RO data are valuable for improving forecasts of high-impact weather events, such as hurricanes, tornadoes, and floods. RO data are also used to monitor and study climate change, and to forecast space weather.

Today, NOAA produces RO data products from its COSMIC-2 low earth orbit (LEO) satellite system, launched in June 2019 with a 10-year design lifespan. To supplement this source, NOAA has also purchased data from commercial weather satellites through the NESDIS Commercial Data Program (CDP). Through CDP, NESDIS performed pilot projects assessing the ability of commercial providers to produce RO data meeting NOAA requirements. After successful completion of the pilot projects (e.g., NOAA/NESDIS 2020), CDP began procuring data for operational use in 2020 through Indefinite Delivery Indefinite Quantity (IDIQ) contracts and has continued to do so at the time of the report.

The process and status of that program has been documented in multiple NOAA reports (e.g., NOAA, 2021). Various challenges have been encountered, with some overcome and some still being resolved. Important examples include sensor failures, licensing constraints that potentially limit free and open data distribution (and the related cost tradeoff to gain such license rights), and the determination of the most cost- and risk-effective timeframe over which data should be purchased.

The notion of a backbone appeared in a 2020 NOAA report on RO[1] and was elaborated on by the independent World Meteorological Organization (WMO) International Radio Occultation Working Group (IROWG; https://irowg.org) for the case of RO data. They suggested that commercial suppliers may be a useful source of RO data under certain conditions, but that any plan for reliable provision of such data include government satellite systems capable of

[1] NOAA (2020) notes: "NOAA's long-term plan is to maintain an RO constellation that includes a government backbone of RO observations, augmented with data from commercial data buys and with data from interagency and international partners."

ensuring a minimum number of such observations, referred to as the "backbone."[2] To further explore this, an ongoing IROWG project called RO Modeling EXperiment (ROMEX) (https://irowg.org/ro-modeling-experiment-romex/) is evaluating the impact of increased numbers of daily RO observations on weather prediction skills.

Important Related Work

This work is related to a number of NOAA-related advisory reports, such as the Science Advisory Board (SAB) Priorities for Weather Research (PWR) report (NOAA SAB, 2021) and the Keck Institute for Space Studies (KISS) report (Abdalati et al., 2023) on climate observations, both of which describe critical needs for observational data. It is also relevant to Section 106 of the Weather Research and Forecasting Innovation Act of 2017 (Public Law 115-25), which directed NOAA to "determine a range of options to address gaps" in observation data.

Study Process and Approach

The Environmental Information and Services Working Group (EISWG) is a working group of the NOAA Science Advisory Board (SAB). The study was initiated by EISWG in recognition of general interest in RO, but the subject evolved to the more general topic of observing system backbones based on needs identified by NOAA. The EISWG study team interviewed representatives from NOAA, WMO, European Centre for Medium-range Weather Forecasts (ECMWF), and commercial data providers. Findings and recommendations reflect common themes from these interviews.

Definitions

The following definitions are central to the discussion in this report.

- *Observational Data Element (ODE).* An observational data element is a portion of NOAA's overall observation needs having common data characteristics[3]. This term generally corresponds to data generated by a particular sensor type. Two examples are RO observation data and ground-based weather radar data.
- *Backbone ODE.* That portion of the ODE which is supplied from sensor systems operated by the government (which may be developed by the government, by its international partners, or by contracted commercial suppliers). A backbone may include

[2] The IROWG-9 workshop summary (IROWG, 2022) included: "IROWG recommends operational Global Navigation Satellite System (GNSS) RO missions for continuous global climate observations to be established and maintained as a backbone to ensure continuity and long-term availability of climate quality RO measurements with global coverage and full local time coverage. IROWG reaffirms our support for publicly funded high-quality observations and also acknowledges the contributions of commercial data providers, pending validation of their climate data quality, including complete long-term access by independent processing centres to the complete set of acquired data without any data removal due to pre-screening. The backbone missions can provide stable, long-term, SI-traceable and reliable observations. The expertise of publicly funded data-processing centres is invaluable in assessing and archiving commercial data provision. They also help to reduce the risk to the global observing system if one or more commercial providers were to go out of business, or if the market became dominated by a single player."

[3] These data-centric definitions for NOAA observations are appropriate for the purpose of this report. NOAA (NOAA, 2016) uses sensor-centric definitions for some purposes. While there are important differences between the data-centric and sensor-centric approaches, they are readily aligned with each other.

spaceborne and/or ground-based observations. In specific cases, sensor systems developed and operated by international partner governmental agencies may be considered by NOAA to be part of the backbone ODE.
- *Alternative-source ODE.* That portion of the ODE supplied from alternative sources. The important current example is satellites that are commercially developed and operated, but it is appropriate to generalize the potential sources beyond commercial providers.

Generalized Applicability

While this report reflects the initial charter to address needs within NESDIS for spaceborne observations, the recommendations can be reasonably extended to address similar needs throughout NOAA. An important example is ground-based weather radar data. While the notion of a backbone did not exist when the current NOAA weather radar system was built, it may be applicable to the current situation. The existing system has coverage gaps, for which various solutions have been proposed going back many years. It is reasonable to position the existing system as a backbone, with augmentations and additions (potentially from commercial sources) used to fill in gaps and make targeted improvements. Similarly, the NOAA system of weather stations could be considered a backbone for the larger system of weather stations that includes mesonets operated by various government and commercial organizations (e.g., National Research Council, 2008). The growing number of sources for alternative-source ODE provides a strong motivation for applying the backbone framework more broadly across NOAA.

References

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- NOAA, Report to Congress: Radio Occultation Data Gap Mitigation Plan, 2020.
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- NOAA Science Advisory Board, 2021: A Report on Priorities for Weather Research. NOAA Science Advisory Board Report, 119 pp.
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FINDINGS AND RECOMMENDATIONS

<u>The Opportunity</u>. NOAA indicated to the study team that access to alternative-source data is desirable and that the concept of a backbone could contribute to successfully accomplishing that.

FINDING 1. For a variety of important reasons, such as performance and/or cost benefits, NOAA has a growing interest in integrating alternative-source observations (notably commercial but could include other providers such as non-governmental organizations) in its system portfolio. This interest varies by ODE.

FINDING 2. Availability of alternative-source observations for a particular ODE system element may or may not eliminate a need for NOAA to make similar observations. In cases where an ongoing NOAA role is needed, the NOAA element can be referred to as a "backbone." It may serve one or more functions (as described in Appendix A), with the overall goal of ensuring a programmatically, scientifically, and technically robust ODE.

RECOMMENDATION 1. NOAA should employ a backbone approach to integrating alternative-source observations, with the nature of that backbone determined through a process involving a formal decision and implementation framework.

<u>Proposed Backbone Framework</u>. Given this opportunity, and the suggestion for a formal process to define the backbone, the study team determined that a comprehensive approach could be based on a framework structured around the following three guidelines:

1. *FRAMEWORK GUIDELINE 1: Employ a Data- and Use-Oriented Systems Approach*
2. *FRAMEWORK GUIDELINE 2: Design the Backbone as an Enabler for All Related Data*
3. *FRAMEWORK GUIDELINE 3: Continuously Assess and Mitigate Risks of Alternative Data*

The findings and recommendations that follow are organized using the framework established by these three guidelines.

GUIDELINE 1. Employ a Data- and Use-Oriented Systems Approach. The inclusion of non-NOAA data sources in any ODE significantly changes how NOAA optimizes its solution for obtaining that ODE. It implies starting from a data perspective, optimizing overall data sets (multiple sources) for use-driven performance/effectiveness, cost, and risk. For the purpose of this report, "use" primarily refers to uses by operational forecasting centers or NOAA data centers, as key users of NESDIS data, but the meaning is readily broadened as appropriate. Achieving optimum value requires careful attention to a number of issues.

FINDING 3. Inclusion of data from multiple sources for a given ODE is a relatively new opportunity and challenge for NOAA. Doing so effectively requires treating those multiple sources as part of a system, for which the relative role and contribution of each data source can be optimized across performance, cost, and risk. That system thinking should reflect NOAA's increasingly important role as an aggregator and critical supplier of such multi-source data to the weather enterprise and larger community.

FINDING 4. The right performance metrics for multi-source ODE optimization are associated with use-related performance/effectiveness, cost, acquisition ease, and risk. For example, one convenient metric for weather forecasting is the forecast sensitivity to observation impact (FSOI), which reflects considerations such as uncertainty and number of observations.

FINDING 5. Data set stability and continuity is important for users. Assimilating data with new or changing characteristics is time-consuming and risky. For instance, it takes several months to years to develop the assimilation capability of a new ODE for weather forecasting. When implementing an ODE system that includes a backbone, a startup phase (as is currently occurring for RO) is likely needed to encourage supplier capacity and to understand data integration. A goal is to proceed past this startup phase and create a system in which the data sources and characteristics are stable over long periods (5+ years), including comprehensive metadata. For example, this could facilitate the use of such an ODE in reanalysis. Both reanalysis and climate data require data with stable characteristics and without gaps over long (5+ years) periods.

RECOMMENDATION 2. The backbone should be architected and implemented through a process that is data- and use-centric, not sensor- or platform-centric. It should treat backbone and alternative-source observations as a system to be optimized across performance, cost, and risk, recognizing the benefits and risks of each component.

GUIDELINE 2. Design the Backbone as an Enabler for All Related Data. Once NOAA determines that alternate-source data are a useful component of any ODE, the NOAA portion of that ODE takes on a new purpose as compared to traditional NOAA ODE for which the only component is NOAA sensor data. NOAA is no longer simply a source of that ODE, but rather an enabler for the entire ODE system. Carefully defining the characteristics of the backbone so as to optimize and enable this system will have substantial benefits to NOAA.

FINDING 6. An essential part of the backbone role is to be an enabler, ensuring that the overall ODE is optimized and the alternative data contribution is maximized. This can happen in many ways, such as providing cross-calibration among alternative-source providers or filling in the expensive orbits (for diurnal or global coverage) so that alternative-source data can be less expensive.

FINDING 7. While the backbone concept was initially proposed in the context of ensuring a minimum number of observations, this concept can be broadened to reflect many important roles a backbone can perform. Appendix A describes examples.

FINDING 8. Project stability, particularly funding, is valued by providers. Funding stability enables better business cases, lowers cost to the government, and leads to more consistent data (consistent in this case refers to: the consistent availability and consistency of observations as satellites enter and leave orbit; calibration drift (or bias); and negligible differences in random error characteristics among spacecraft).

RECOMMENDATION 3. Observing system elements employing a backbone approach should design and implement the backbone as an enabler for the overall ODE system.

GUIDELINE 3. Continuously Assess and Mitigate Risks of Alternative Data. Ideally, sources of alternative ODE are as reliable and robust as suppliers of simple and widely available standard supplies. A trivial but illustrative example is personal computers, for which the government has confidence that reliable commercial suppliers of sufficient quality exist so there is no need for the government to develop its own source. With weather data, we have not reached this level of commercial maturity for most or all spaceborne ODE and may not for some time, but moving rapidly in that direction is beneficial to NOAA if alternative-source data are desired as a long-term component of NOAA's observational data systems. At least part of the reason is that there are few non-government commercial buyers for observational data matching NOAA's specific data requirements. Critical to full acceptance of alternative-source data is a commitment to free and open data access similar to that of government data[4].

FINDING 9. At this time, few or no sources of alternative spaceborne ODE seem to have robust commercial markets (multiple companies with strong business models and a broad stable customer base), presenting an elevated risk for ongoing availability of such data. This risk will need to be factored into backbone decisions, with the hope that maturing markets will reduce the risk over time.

FINDING 10. Fundamental issues remain regarding alignment of NOAA and commercial interests, such as treatment of open data and international data sharing, although significant progress has been made over the last decade in this area.

FINDING 11. Government budgets for alternative data today are more volatile than for government-funded observation systems, presenting a risk to use of alternative-source data. It is hoped that this will change as use of alternative-source data becomes commonplace.

[4] Free and open data access has long been a challenging issue for alternative-source data, and commercial data in particular. A customer (such as NOAA) planning to buy commercial data and redistribute it openly effectively eliminates the possibility of other paying customers for that data, which necessarily impacts the cost to the original customer as some commercial business models involve higher prices when data are subject to open access. A community priority is for all data to be openly accessible, such that backbone and alternative-source data are on parity with similar characteristics for free and open access. Various policies, such as those of WMO, guide requirements for free and open data access. It is beyond the scope of this report to propose a means for accomplishing such access, but a solution is central to successful backbone frameworks.

RECOMMENDATION 4. A continuous process for assessing and mitigating risks to NOAA's alternative-source data availability and access is a key aspect of any backbone approach. NOAA should define a strategy for accomplishing this to the greatest extent possible, addressing issues noted in the related Findings and others it can identify, recognizing that governments have constraints for influencing the robustness of alternative-source (notably commercial) markets.

Appendix A provides an example of the robustness levels that could be used for this assessment and to evaluate progress with risk management.

<u>The RO Example</u>. This framework can be applied effectively to the case of RO. That is done as an example in Appendix B to provide candidate guidance for the RO system and as a pathfinder for other ODE.

FINDING 12. The example of RO provides an excellent pathfinder for other ODE, but it is likely not a typical example. Among other things, RO's ease of cross-calibration makes working with multiple providers simpler than is likely with other ODE. The small, relatively simple instruments, and their consequent advantage to business cases, may also be atypical. Implications of these differences for other backbones are important.

Appendix B, which includes a sample application of the Appendix A framework as applied to RO, motivates the following recommendation.

RECOMMENDATION 5. The backbone approach is applicable to RO, with important backbone roles apparently as yet unfulfilled by alternative-source providers, and NOAA should plan the RO element to include a backbone.

APPENDIX A: Sample Backbone Architecture Decision Matrix

The need for and purpose of a NOAA backbone will be different for each system element. Assessment of the backbone need and purpose can be done using two dimensions:

1. The robustness of the alternative-source data provider market.
2. The expected role of the backbone in the system element.

We can define four levels of robustness:

- *Level 0.* No operationally capable alternative-source data suppliers, and evidence that a commercial market is unlikely.
- *Level 1.* No operationally capable alternative-source data suppliers, but some pre-operational suppliers exist with plans and even limited pilot or evaluation data.
- *Level 2.* One or several operationally capable alternative-source data suppliers. Some or all suppliers may not be able to meet all NOAA requirements. Supplier viability may be heavily dependent on government contracts, with limited non-government alternative buyers. Some risk that the supplier ecosystem will go away.
- *Level 3.* Multiple operationally capable alternative-source data suppliers and robust non-government alternative market. Most or all suppliers can meet all NOAA requirements.

Candidate backbone roles include:

1. *Minimum Data Set.* NOAA may establish a need for ensuring a minimum data set for a given system element, such as a minimum number of atmospheric soundings. The backbone would ensure this minimum data set.
2. *Unaddressed Space/Time Regimes Data.* Alternate data sources may not fully cover the needed space/time regimes. For example, they can be motivated to provide data only from orbits associated with lowest-cost launches.
3. *Anchor Data.* NOAA may use one data set to "anchor" others, such as use of balloon sounding data to help eliminate biases in satellite sounding data. The ability to perform this anchoring may require a backbone element if the corresponding alternative-source data can't perform that role.
4. *Calibration and Cross-Calibration Data.* NOAA may have calibration needs that are not fully met by alternative-source data. Calibration can require sensors with higher precision, greater stability, or other characteristics. In addition, when data from multiple providers have differing characteristics, a backbone system can perform the role of cross-calibration so that multiple data sets can be used effectively.
5. *Reference Standard Data*. For some ODE, the data characteristics will vary from one alternative-source provider to another. Moreover, there is also the potential for data characteristics to change over time for each provider. While such differences may be acceptable, it may be important to have a reference standard data set for which characteristics either don't change or change in accepted ways. The backbone element can provide this.

6. *Climate-Quality Data*. Climate-quality data often have data characteristics that are more stringent than needed for weather purposes. A backbone may ensure the data meet climate standards.
7. *Data Continuity*. Continuity of data sets is important for climate work as well as for weather reanalysis data (see Abdalati et al, 2023).
8. *Observation Quality*. Use of a backbone can enhance the overall quality of the data set, should the available alternative-source data not have sufficient quality by itself.
9. *Observation Cost & Cost Risk*. Inclusion of backbone data can make it possible for lower cost and/or higher risk alternative-source data to be used when the alternative-source data by itself may be insufficient.
10. *Research Access to Data.* A backbone can ensure access to data of research quality when alternative-source data has quality, access, or licensing characteristics that don't support research needs.
11. *Equitable Data Availability.* A backbone can help ensure that data are collected and available in a manner that is fully equitable for all end-users, particularly those that may be underserved otherwise.
12. *Open Data Access.* A backbone may provide data with open data access, particularly as needed to be consistent with WMO or other policy directives.

For any given system element, one or more of these roles may justify development of a backbone component for the observing system element. The following table can be used to assess the need for and role(s) of the backbone.

	Market Robustness Level (R=required, D=desirable)			
Backbone Role	Level 0	Level 1	Level 2	Level 3
1. Minimum Data Set				
2. Unaddressed Space/Time Regimes Data				
3. Anchor Data				
4. Calibration and Cross-Calibration Data				
5. Reference Standard Data				
6. Climate-Quality Data				
7. Data Continuity				
8. Observation Quality				
9. Observation Cost & Cost Risk				
10. Research Access to Data				
11. Equitable Data Availability				
12. Open data access				

Completion of the table defines which backbone roles are needed at each market robustness level. An example of this table filled in for the RO element is included in Appendix B.

APPENDIX B: Case Study – Radio Occultation

This appendix applies the framework to RO (a relatively mature example of commercial observations within the NOAA system), as an example for use of the framework. Entries in the table are examples, with NOAA's version likely to differ based on access to additional considerations. For RO, a COSMIC-like follow-on could perform the role of a backbone. The current COSMIC system has performed this backbone role to some extent, providing an example of the purpose and utility of the backbone approach.

Backbone Role	Market Robustness Level (R=required, D=desirable)			
	Level 0	Level 1	Level 2	Level 3
1. Minimum Data Set	R	R	R	-
2. Unaddressed Space/Time Regimes Data	R	R	R	-
3. Anchor Data	D	D	D	-
4. Calibration and Cross-Calibration Data	D	D	D	-
5. Reference Standard Data	R	R	D	D
6. Climate-Quality Data	R	R	D	-
7. Data Continuity	R	R	D	-
8. Observation Quality	R	R	D	-
9. Observation Cost & Cost Risk	R	R	D	-
10. Research Access to Data	R	R	D	-
11. Equitable Data Availability	R	R	D	-
12. Open data access	R	R	D	-

The table indicates that a backbone is required for the RO ODE for Market Robustness Levels 0-2 and desirable for Level 3.