PERFORMANCE TRAJECTORIES OF EARTH OBSERVATION TECHNOLOGIES: PARAMETERIZED FORMULATIONS AND ESTIMATION

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ABSTRACT

Since the first spacecraft were deployed for earth observation (EO) in the early 1960s, technological change in EO systems has significantly improved remote sensing capabilities. To fully understand the pace of past change and develop empirical baselines for future projections, it is important to quantitatively characterize performance of key instruments used in EO missions. This study presents trends in performance in EO instruments using empirical data from spacecraft and instruments deployed from 1959-2022. Parameterized models are derived to quantitatively determine temporal progression in key figures-of-merit. Pareto frontiers of mass and resolution of sounders, SAR, and radiometers are also determined. The results show a consistent shift in Pareto frontiers of radiometers across successive 15-year periods spanning 1972 to 2025.

Index Terms— earth observation, technology roadmapping, sounders, SAR, radiometers

1. INTRODUCTION

Since the first spacecraft were deployed for earth observation (EO) in the early 1960s, technological change in EO systems has significantly improved remote sensing capabilities. To fully understand the pace of past change and develop empirical baselines for future projections, it is important to quantitatively characterize key technologies at various levels, including components, instruments, and spacecraft [1].

Approaches to characterize technology progression include Wright's law [2], which was developed based on observations of aircraft manufacturing, and subsequent work by others to characterize effects of cumulative production on unit costs. This approach has led to the development of the 'learning curves' method to estimate changes in costs due to learning and improved efficiency in production processes. Another popular method is described by Moore's Law [3], which was based on empirical observations on progress of density of components in semi-conductor chips and computation capabilities. Research in a variety of technologies including energy and air transportation [4] has provided useful models to understanding technology progression in these domains.

In case of earth observation technologies and for many scientific missions and instruments, the number of produced units remains small. Each mission involves new technology, new advances in instrumentation and measurements, and embodies an innovation frontier in technology performance. Different models are needed that meaningfully represent performance (and cost) change over time in such cases. This work focuses on characterizing performance trends and Pareto frontiers in selected key earth observation instruments using empirical data of instruments deployed from 1959-2021.

2. PARAMETRIC MODELS OF TECHNOLOGY TRENDS

Several previous studies have contributed parametric models using empirical data for computing key performance measures for spacecraft and payloads. An extensive set of models were provided in [5] that consisted of both physics-based as well as empirical relationships. An early study contributed parametric scaling models for nongeosynchronous (NGSO) communications satellites [6]. The study used response surface method (RSM) to obtain scaling relationships among system-level parameters. A subsequent study developed relationships for estimating earth observation payload mass and power based on spacecraft wet mass and power and differentiated by spacecraft orbit [7]. Other studies on historical and future trends have discussed energy intensity for aircraft [4], trends in small sats [8], markets in earth observation [9], changes in architecture for observing systems[10], and trends in transportation and communication technologies [11]. This work relates to this previous literature with a focus on a selected set of earth observation instruments. It also builds from, and complements, recent work that quantifies performance trends of EO imaging instruments [1, 12].

2.1. Parametric Models for EO technologies

The generalized approach used in this work (described in more detail in [12]) is based on identification of a set of figures-of-merit (FOM) that characterize functional capabilities [11]. The trends in FOM of a technology are determined from the best performers (or the so-called "record setters") over time [13]. Figure 1 shows this conceptually where trend in a FOM is determined by only analyzing the empirical data that represents the "best" (in this case lowest) FOM at each time t_i. If the trend is determined to be statistically valid, it can be projected to a future time to establish a baseline expectation.

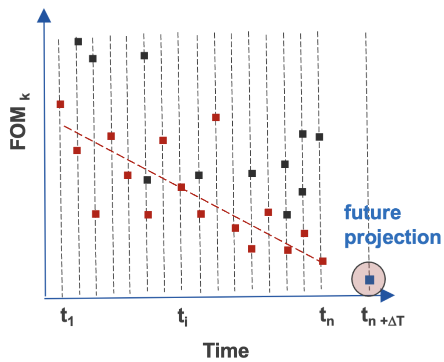

Fig. 1. Trends in technical capability can be quantified based on "best" figures-of-merit over time

3. RESULTS: PERFORMANCE TRENDS

Instrument and spacecraft data was collected from a number of databases: the NSSDCA database [14], Seradata's satellite database [15], WMO OSCAR[16], and ESA's eoPortal. The combined database consisted well over 4900 spacecraft and 1050 different instruments flown from 1957-2023. Spacecraft were selected to be included in the database if their primary mission was related to Earth Observation.

3.1. Temporal trends in instrument mass

Mass is an important metric, and often a proxy of cost in space systems. The mass of different instrument types was analyzed to determine trends over time. Fig. 2 shows minimum, maximum, and average mass (of different instruments) launched each year. The best fit models obtained from the entire period (1964-2026) do not yield high R2 values (as shown in Table 1). This is partly due to a shift in trends, wherein minimum (and average) mass of launched instruments initially increased and after some period it subsequently decreased (or stabilized) over time. A detailed discussion of shift in spacecraft mass trends is provided in [12] and [1]. Here, instruments mass data shows a similar trend wherein average and minimum mass increases in time from 1960s till 1990s. The following decades since 1990s exhibit a reduction or stabilization. Interestingly, this empirical data shows the miniaturization trend that has been prominent in space technologies

Instrument Class	Best Fit	P-Value	R2
Imagers	$18.20 * e^{(0.03x)}$	<0.0001	0.53
Radiometers	$26.86 * e^{(0.02x)}$	0.0237	0.17
SAR	$184.37 * e^{(0.03x)}$	0.0518	0.20
Sounders	$18.20 * e^{(0.04x)}$	<0.0001	0.49

Table 1. Regression fit of average mass vs. time for selected instrument classes, where x is years since 1960.

and has been subject of interest due to its implications for future cost reductions.

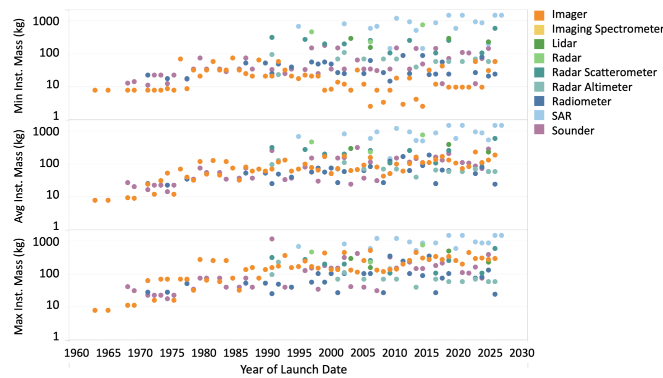

Fig. 2. Minimum, average, and maximum mass in kg for each category of instrument launched by year

3.2. Temporal trends in instrument resolution

Best resolution is also an important figure-of-merit (FOM) for EO instruments, and its trends were analyzed for different instruments. Figure 3 shows minimum resolution (by type of instrument) launched by year. The best fit models (shown in Table 2 show a strong temporal trend for imagers (low p-value and high R2 value).

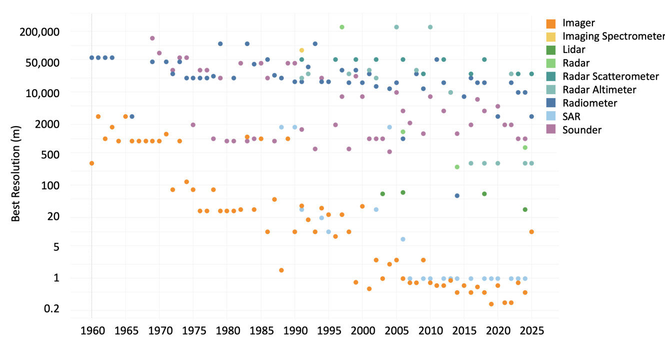

Fig. 3. Best instrument resolution in m for different types of instruments launched by year

Instrument Class	Best Fit	P-Value	R2
Imagers	$1358 * e^{(-0.14x)}$	<0.0001	0.80
Radiometers	$51342 * e^{(-0.03x)}$	0.0005	0.23
SAR	$13654 * e^{(-0.16x)}$	0.0001	0.52
Sounders	$(1.01 * 10^6) * x^{-1.54}$	0.0002	0.26

Table 2. Regression fit of best resolution vs. time for selected instrument classes, where x is years since 1960.

Instrument Class	Best Fit	P-Value	R2
Imagers	$898 * e^{(0.11x)}$	<0.0001	0.46
Radiometers	$0.08 * e^{(0.11x)}$	0.0003	0.34
SAR	$4602 * e^{(0.08x)}$	0.0054	0.41
Sounders	$0.09 * e^{(0.18x)}$	<0.0001	0.61

Table 3. Regression fit of maximum instrument data rate vs. time for selected instrument classes, where x is years since 1960.

3.3. Temporal trends in instrument data rates

Instrument data rates are another important FOM, and its trend was also empirically investigated. Figure 4 shows the maximum data rate of instruments flown each year, and a generally increasing trend is visible for most instrument types. Table 3 shows the best-fit models.

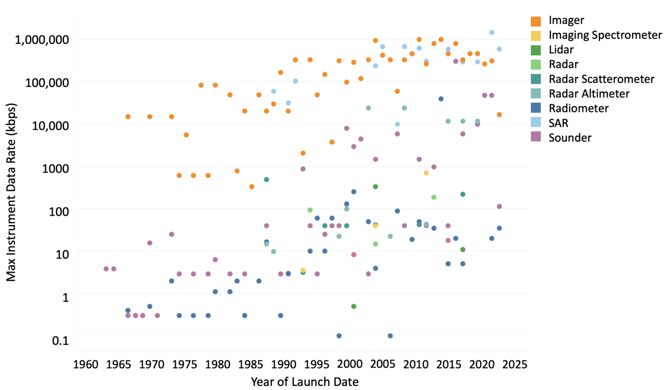

Fig. 4. Maximum instrument data rate in kbps for each category of instrument launched by year

4. RESULTS: PARETO FRONTIERS

The figures-of-merit, such as mass and resolution, of instruments were used to construct Pareto frontiers for different instrument types. A Pareto frontier between two FOMs shows the best value achieved for one FOM for a given level of the other FOM [11]. Since the data used in this analysis is of instruments built and launched, the empirically constructed Pareto frontiers essentially show the 'state-of-the-art' (SOA) achieved for particular FOMs. The figures in this section show the Pareo fronts obtained for different instrument types.

It should be noted that only data records for which both FOM (such as mass and resolution) data was available were used. Record entries for which one or both of this information was missing are not represented.

Figure 5 shows the Pareto frontier of mass and best resolution of sounders. The data records of sounders, available for this analysis, spanned 1969-2024. Each dot represents a sounder (of particular mass and resolution). The instruments constituting the Pareto frontier are marked with connected stars. These are labeled with instrument name, associated agency, and launch year.

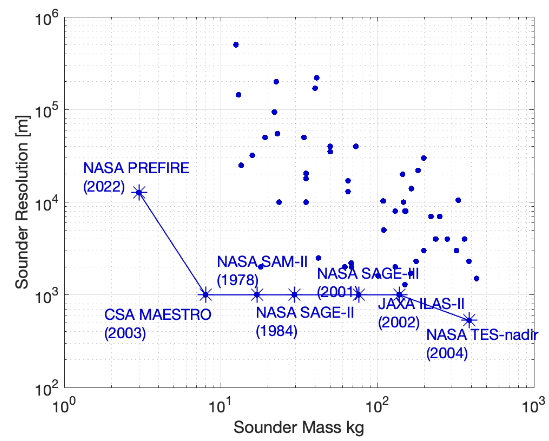

Fig. 5. Empirically constructed Pareto frontier (marked with connected stars) of resolution and mass for sounders launched between 1964-2024.

Figure 6 shows the Pareto frontier of mass and best resolution of Synthetic Aperture Radar (SAR) instruments.

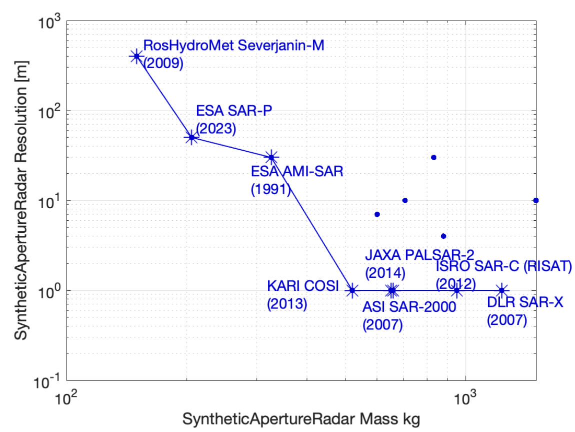

Fig. 6. Empirically constructed Pareto frontier (marked with connected stars) of resolution and mass for SAR instruments launched between 1991-2023.

Figure 7 shows the Pareto frontier of mass and best resolution of radiometers. The data records spanned launch years of 1972-2025. In this case, the data was partitioned into three successive periods and the pareto frontier of each period was separately determined (and is shown in Fig. 7). It is interesting to note that the Pareto frontier shifts closer to the origin in each period, indicating a consistent trend in miniaturization. This trend, of temporally shifting pareto frontiers, was not as obvious for SAR and sounders.

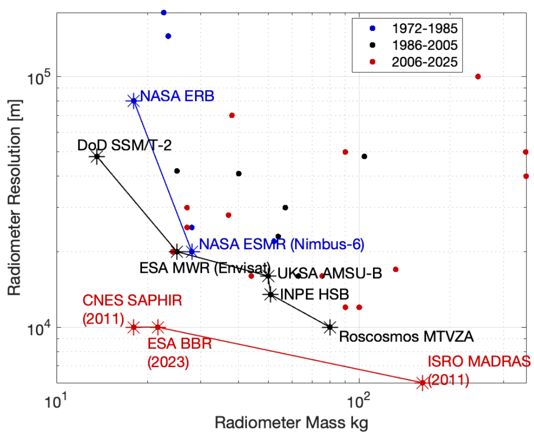

Fig. 7. Empirically constructed Pareto frontier (marked with connected stars) of resolution and mass for radiometers. Three successive periods are shown marked in different colors.

5. DISCUSSION

This work advances research on characterizing technology trends in earth-observation. The instrument-level analysis, in particular of sounders, SAR, radiometers, and imagers launched on spacecraft for earth observation missions since 1957, shows some shifting and some consistent trends in time. The mass of instruments initially increased in early years of the space age - there was a trend of building bigger, heavier payloads and spacecraft. Since the end of the 20th-century, however, the trend has somewhat reversed or stabilized. In some cases, the reversal has been highly pronounced as can be observed in miniaturization trend of radiometers. Overall, these results connect with on-going efforts [1, 12] for quantifying historical progression, identifying state-of-the art, and projecting for future baselines that can collectively inform earth observation technology roadmapping and investment efforts. Additionally, insights from progression models can aid investment decisions for remote sensing systems [17] that are increasingly of interest for enhancing critical decisions for development.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] A. Siddiqi, J. Milton, G. Lordos, and O. De Weck, "Trends and technology roadmapping in earth observation missions," in *IGARSS 2022-2022 IEEE International Geoscience and Remote Sensing Symposium*. IEEE, 2022, pp. 7174–7177.

[2] T. P. Wright, "Factors affecting the costs of airplanes," *Journal of Aeronautical Sciences*, vol. 10, pp. 302–328, 1936.

[3] G. E. Moore, "Progress in digital integrated electronics," in *International Electron Devices Meeting*, no. September, 1975, pp. 11–13.

[4] J. J. Lee, S. P. Lukachko, I. A. Waitz, and A. Schafer, "Historical and future trends in aircraft performance, cost, and emissions," *Annual Review of Energy and the Environment*, vol. 26, no. 1, pp. 167–200, 2001.

[5] W. J. Larson, J. R. Wertz *et al.*, *Space mission analysis and design*. Springer, 1992, vol. 3.

[6] P. N. Springmann and O. L. De Weck, "Parametric scaling model for nongeosynchronous communications satellites," *Journal of spacecraft and rockets*, vol. 41, no. 3, pp. 472–477, 2004.

[7] J. K. Graham and O. L. D. Weck, "Parametric Sizing Equations for Earth Observation Satellites," *Journal of Spacecraft and Rockets*, vol. 56, no. 2, pp. 476–484, 2019.

[8] D. Selva and D. Krejci, "A survey and assessment of the capabilities of Cubesats for Earth observation," *Acta Astronautica*, vol. 74, pp. 50–68, 2012.

[9] G. Denis, A. Claverie, X. Pasco, J.-P. Darnis, B. de Maupeou, M. Lafaye, and E. Morel, "Towards disruptions in Earth observation? New Earth Observation systems and markets evolution: Possible scenarios and impacts," *Acta Astronautica*, vol. 137, pp. 415–433, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0094576516313492

[10] D. Maciuca, J. Chow, A. Siddiqi, O. de Weck, S. Alban, L. Dewell, A. Howell, J. Lieb, B. Mottinger, J. Pandya *et al.*, "A modular, high-fidelity tool to model the utility of fractionated space systems," in *AIAA SPACE 2009 Conference & Exposition*, 2009, p. 6765.

[11] O. L. deWeck, *Technology Roadmapping and Development: A Quantitative Approach to the Management of Technology*. Springer, 2022.

[12] A. Siddiqi, J. Milton, M. Cabrera, and O. deWeck, "Earth observation technologies for climate change adaptation and monitoring: Future projection from decadal trends," in *International Astronautical Federation (AF)- The Global Space Conference on Climate Change 2023*. IAF, 2023.

[13] C. L. Magee, S. Basnet, J. L. Funk, and C. L. Benson, "Quantitative empirical trends in technical performance," *Technological Forecasting and Social Change*, vol. 104, pp. 237–246, 2016.

[14] NASA-NSSDCA, "Nasa space science data coordinated archive." [Online]. Available: https://nssdc.gsfc.nasa.gov

[15] Seradata, "Sera database." [Online]. Available: https://www.seradata.com

[16] WMO, "Wmo-observing systems capability analysis and review." [Online]. Available: https://space.oscar.wmo.int

[17] A. Siddiqi, S. Baber, and O. De Weck, "Valuing radiometric quality of remote sensing data for decisions," in *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS*. IEEE, 2021, pp. 5724–5727.