

An Unrivaled Asset: The NASA ER-2 as a Driver of Unique Scientific Innovation

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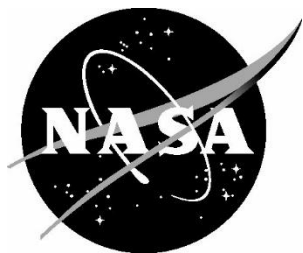
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Abstract

The NASA ER-2 is a purpose-built version of the USAF U 2R high-altitude aircraft. The ER 2 is capable of delivering over one ton of instrument payload to altitudes approaching 70,000 ft, well into the stratosphere, at subsonic speeds for an eight-hour flight. These aircraft uniquely enable a number of mission profiles important to NASA including targeted remote sensing and in-situ science, satellite calibration and validation, and instrument technology maturation. The missions flown by these aircraft have been at the core of numerous ground-breaking discoveries, including the conclusive demonstration of the connection between chlorofluorocarbons (CFCs) and the Antarctic ozone hole, as well as the discovery of novel electrical phenomena tied to thunderstorms. In both these examples, the discoveries that resulted from the ER 2 flights were only possible because of the unrivaled flight altitude of the ER-2. This manuscript, written based on collected responses from a community survey of the scientists, engineers, and crew who have been involved with these aircraft, examines the unique history, strengths, and weaknesses of the NASA ER-2 as a driver of unique scientific innovation.

Survey Respondents

John Arvesen, Monte Bateman, Fran Becker, Kenneth Bowman, Scott Braun, Paul Bui, Daniel Cecil, Estelle Condon, Mike Craig, Philip Dennison, David Diner, Rose Dominguez, David Fahey, Antonia Gambacorta, Steven Goodman, Jeffrey Halverson, Gerald M. Heymsfield, Steven Hipskind, Olga Kalashnikova, Kirk Knobelspiesse, Timothy Lang, Allen M. Larar, Douglas Mach, Matthew McGill, Christopher Mertens, Nikolai Østgaard, Stephen Palm, Walt Peterson, Lenny Pfister, Mason Quick, Andrew Roberts, Andrew Sayer, Susan Strahan, O. Brian Toon, Adrian Tuck, Woody Turner, Kevin Turpie, Timothy Williams, David Wilmouth, John Yorks, and Michael Zolensky

1. Introduction.....	3
2. A Brief History of ER-2 Missions	3
3. The Unique Significance of the ER-2 in Addressing Science and Instrument Development Needs	6
4. The Challenges of the ER-2 from a Mission Science Perspective.....	7
5. Conclusions.....	8
6. References.....	9

1. Introduction

The NASA Earth Resources 2, or ER-2, is a modified civilian version of the US Air Force (USAF) U-2R aircraft and is capable of carrying 2,550 lbs. of instrumentation to altitudes approaching 70,000 feet (70 kft) for missions lasting up to eight hours. Prior to the ER-2 program, NASA relied on two U-2C aircraft loaned from the USAF in 1971, for satellite simulator and in-situ stratospheric sampling missions. Prompted by the USAF phasing out their U-2C aircraft, NASA acquired its first ER-2 in 1981 and a second ER-2 in 1988, with the ER-2s representing a direct upgrade to the capabilities provided by the U-2Cs. In addition to the two NASA-owned ER-2s, NASA operated a third ER-2, converted from a U-2 on loan from USAF, from the late 1980s until the aircraft was returned to USAF in 1997. Since their arrival at NASA, the ER-2s have been in high demand and have taken part in a wide variety of missions in support of science, engineering, and disaster response.

As the highest altitude research aircraft in the world, the unique capabilities of the ER-2 have enabled ground-breaking discoveries that would not have been possible with other aircraft. While the demand for the ER-2s remains high, the aircraft face an uncertain future due to the planned end of the USAF U-2 program. Without the ongoing supply chain and engineering supporting the USAF U-2 program, the cost for NASA to continue the ER-2 program will substantially increase. A review of the ER-2, independent of this effort, that aimed to evaluate possible replacements for the ER-2 and identify capabilities that would be lost if the aircraft were retired without a replacement took place in 2025. Their review found that, although there are other platforms that can cover specific aspects of the ER-2's science missions, no other platform is able to match the ER-2's full capabilities (personal communication, Ozoroski and Bennett 2026).

This paper aims to explain the strengths and weaknesses of the ER-2, in terms of their use as a science and instrument development platforms, from the point of view of the scientists and engineers who have worked with these unique aircraft. The contents of this paper are based on responses to a survey of people who have been involved with the aircraft via science, instrument development, and operations. The survey included questions related to the respondents' involvement with the aircraft, the benefits of its unique capabilities, and the challenges involved with the aircraft. For convenience, we have grouped our synthesis of these responses into several sections. Section 2 will highlight a subset of the missions the aircraft have flown. Sections 3 and 4 will discuss the strengths and weaknesses, respectively, of the aircraft as platforms for both science and instrument development. Finally, section 5 will provide conclusions.

The community responses strongly attest to the importance of the NASA ER-2 aircraft to NASA's mission to understand the Earth, the atmosphere, and space. The combination of the altitude, endurance, air speed, and payload capabilities of the ER-2 represents a critical capability that only NASA is able to provide, is wholly unique to the ER-2, and continues to be in high demand both for science and instrument development.

2. A Brief History of ER-2 Missions

A wide variety of field campaigns and one-off missions have leveraged the ER-2's unique capabilities, including campaigns originating both internally to NASA and from external partners, in support of disaster response, science, satellite validation, and airborne and spaceborne instrument development. The missions include flights of just a single ER-2 on its own as well as numerous examples where the ER-2 has flown in close coordination with other aircraft, both NASA and non-NASA.

Throughout the U-2 and ER-2 programs, NASA Ames Research Center, the original home of the program, maintained a collection of facility instruments (primarily cameras and visible and infrared imagers) that

could be installed on the aircraft at short notice. This enabled the ER-2 to fly rapid response missions on short notice, a capability that has enabled the ER-2 to be deployed in support of disaster monitoring and response. While the majority of the ER-2 disaster response flights have been in response to wild fires, primarily in the western United States, disaster response flights have been flown in response to ecological disasters, including the Deepwater Horizon oil spill in the Gulf; earthquakes, tornadoes, and flooding, including the record-breaking flooding on the Mississippi River in July and August 1993; hurricanes, including damage assessment flights over Florida the day after Hurricane Charley made landfall in 2004; and even a flight to locate fragments of a meteor that exploded in the upper atmosphere over northern British Columbia in January 2000. Additionally, an ER-2 flew a search mission looking for debris following the Columbia space shuttle disaster, although that flight occurred three weeks after the disaster.

One of the most notable discoveries that can be attributed to the ER-2 program is the establishment of a link between human-produced chlorofluorocarbons (CFCs) and stratospheric ozone destruction responsible for the Antarctic ozone hole. The 1987 Airborne Antarctic Ozone Experiment (AAOE) field campaign was formulated to take in-situ observations of the ozone hole. At this time, there were three hypotheses on the cause of the severe Antarctic ozone decrease. The ER-2 in-situ instruments were chosen to specifically test these hypotheses. The ER-2 observations conclusively demonstrated that Antarctic ozone depletion resulted from chlorine and bromine released from human-produced CFCs and bromine containing halons (Anderson et al., 1989). The observations also definitively showed that the other two hypotheses were wrong. Figure 1 shows two key ER-2 latitude profiles of ClO (blue) and O₃ (red) between 23 August (left) and 16 September 1987 (right). Under the alternative hypotheses, ClO would have only reached levels of 0.1 ppbv, but these observations showed levels 2-10 times larger than were predicted from the chlorine/ozone hypothesis. Further, ozone concentrations declined substantially over the course of the mission, and the ClO/ozone data became anti-correlated (high ClO and low ozone with low ClO and high ozone) as the ozone hole developed. These findings resulted in a strengthening of the Montreal Protocol to control the production and consumption of ozone depleting substances (ODSs). Arctic missions with the ER-2 in 1988-89 (AASE-I) and 1991-92 (AASE-II) followed AAOE and showed that these same chemical processes were occurring in the Arctic, leading to additional amendments to the Montreal Protocol that led to the eventual full controls of ODS production and consumption. The ER-2's range and high-altitude capability were critical to verifying this CFC-ozone hypothesis, and the results would not have been so conclusive without the ER-2.

There have been numerous field campaigns focusing on thunderstorms (e.g., the CAMEX series, CRYSTAL-FACE, TRMM-LBA), hurricanes (e.g., TCSP), and winter storms (e.g., IMPACTS) that flew the ER-2. On most of these missions, the ER-2 was extensively outfitted with remote sensing instruments that were flown well above the troposphere. For example, during CRYSTAL-FACE, the ER-2 had 11 instruments that included: two Doppler radars, a cloud/aerosol lidar, a microwave temperature profiler, a sub-millimeter microwave radiometer, a dropsonde system, in-situ meteorological observations, an in-situ water instrument, a spectral flux radiometer, a radiation measurement system, and the MODIS airborne simulator. No satellite ever flown has included such a complete set of remote sensing instruments. The ER-2 fundamentally performs as a steerable and reconfigurable major observatory satellite. The data collected by the instruments aboard the ER-2 during these campaigns have been used in numerous studies that have fueled the advances in our understanding of Earth's weather.

A recent instance of breakthrough scientific achievements that can be directly attributed to the unique capabilities of the ER-2 occurred as a result of the Airborne Lightning Observatory for FEGS and TGSs (ALOFT, Lang et al. 2025) field campaign in 2023. The ALOFT field campaign was designed to examine terrestrial gamma-ray flashes (TGFs) and gamma-ray glows produced by strong thunderstorms. Prior to the ALOFT field campaign, these flashes and glows were only rarely observed, and the science team was hopeful that the instruments might observe one or two during the campaign. Over the course of 10 flights over Florida, Central America, and the Caribbean Sea, the instruments carried aboard the ER-2 observed a

total of 138 TGFs and 361 gamma-ray glows during straight and level flight. Among numerous publications, the flights resulted in a pair of publications in the highly prestigious journal *Nature*: one on the finding that these phenomena are far more common than previously expected (Marisaldi et al. 2024) and one covering the discovery of a new phenomenon identified in the ALOFT data called a flickering gamma-ray flash (Østgaard et al. 2024). Due to the extreme height of these thunderstorm tops, the ER-2 is the only research aircraft in the world that is capable of collecting these groundbreaking observations.

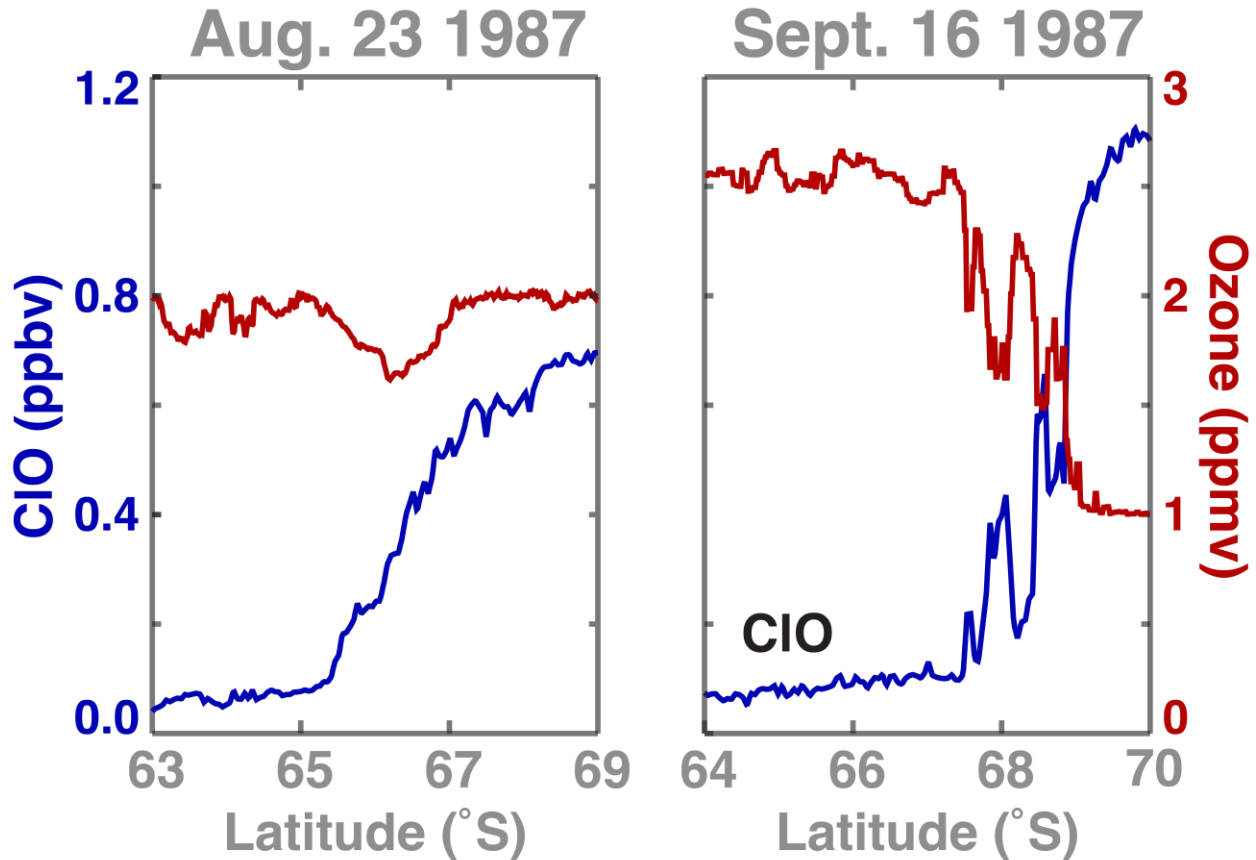


Figure 1. NASA ER-2 flight data at ~18.5 km for CIO (blue) and ozone (red) on 23 August 1987 (left) and 16 September (right) as a function of latitude. Adapted from Anderson et al. (1989) Figures 1 and 13.

The impacts of the ER-2's missions also extend beyond science and instrumentation. Since 2023, the ER-2 has been flying as part of the Geological Earth Mapping Experiment (GEMx) field campaign, a joint field campaign by the U.S. Geological Survey and NASA (<https://science.nasa.gov/mission/gemx/>). GEMx aims to map critical untapped mineral resources in the United States, including rare earth elements such as lithium. Including the flights in 2025, GEMx has taken observations at 15-m or better resolution over more than 800,000 km² of the United States, including parts of California, Nevada, Oregon, Idaho, Utah, Arizona, New Mexico, and Texas (Jones et al. 2026). The findings that result from these flights have direct strategic and commercial benefits for the country.

The influence of the ER-2 also extends beyond Earth science. The Large Area Cosmic Dust Collector is an instrument that has flown on the ER-2 semi-regularly. The instrument is designed to collect tiny particles of cosmic dust that constantly fall into Earth's atmosphere. The dust can then be studied by scientists on the ground to provide insights into the history of our solar system. Additionally, many of the microanalysis

techniques developed to analyze these samples have since been used to analyze the samples returned by the OSIRIS-REx asteroid sample return mission.

3. The Unique Significance of the ER-2 in Addressing Science and Instrument Development Needs

The ER-2's ability to deliver approximately 1.275 tons (2,550 lbs) of instrument payload well into the stratosphere at subsonic speeds for eight-hour flights uniquely enables several important mission profiles, examples of which include targeted remote sensing and in-situ science, satellite calibration and validation, and instrument technology maturation. While the operating altitude of the aircraft is payload and mission dependent, the cruising altitude at the start of a flight is typically no lower than 60,000 ft and often exceeds 65,000 ft; this altitude will gradually increase over the course of a flight, up to a maximum of 70,000 ft, due to fuel burn lessening the aircraft weight. Because the ER-2 is capable of ascending to and descending from its cruising altitude very rapidly, almost seven hours of the ER-2's eight-hour flight endurance can be dedicated to science operations from within the stratosphere. Once at cruising altitude, the aircraft are capable of providing a very stable observing platform (either in altitude or attitude as dictated by mission needs), a quality that can be of great importance for certain types of remote sensing. Furthermore, the subsonic air speed results in improved horizontal resolutions for remote sensing measurements and avoids the potentially sample-destroying heating produced when stepping down the air flow from supersonic speeds for in-situ measurements.

Approximately 91% of the Earth's atmosphere, by mass, is below 60,000 ft (~95% is below 70,000 ft). With the vast majority of the atmosphere below the aircraft, validating satellite remote sensing data using ER-2 instruments is greatly simplified. Furthermore, because the ER-2 is able to penetrate further into the stratosphere than other aircraft, trace gas (e.g., ozone) measurement missions are able to reach locations with higher concentrations (Fig. 2), which is key for establishing reliable measurements due to the higher signal to noise ratios. Another benefit of the ER-2's high altitude environment is that the conditions are well suited for preventing electrical charge build-up on the aircraft. As a result, the ER-2 is a good platform for collecting electrically sensitive measurements, such as measurements of the electrical field around thunderstorms made by NASA's Lightning Instrument Package (LIP, Bateman et al. 2007).

The high altitude is irreplaceable when overflying deep convection as aircraft at lower altitudes must divert around the thunderstorm updrafts for safety reasons. While some instrument designs may allow for viewing deep convection from the side, the microphysical properties (e.g., ice crystal shape and orientation) of precipitation and cloud particles mean that the remote sensing data is very dependent on the viewing angle. As such, the ability to view the convection from above is critical to the development and validation of satellite instruments and algorithms. A recent report on the future direction of research in clouds and convection (Braun et al. 2025) highlighted the importance of studying these intense thunderstorms with multiple domestic and international satellite missions (e.g., NASA INCUS, ESA EarthCARE) targeting these features. Even for instruments observing low-altitude or surface features, the higher altitude is highly valued due to the increased swath width provided; when combined with the long flight duration, the wider swath width means that an ER-2 flight can cover a considerably larger area than would otherwise be possible.

The long flight endurance and range of the ER-2 also means that the aircraft can deliver the sizable instrument payload to more distant targets or sample multiple targets in a single flight. This capability is ideal when targeting a moving weather system over the course of multiple days, such as the hurricanes targeted by the NASA Tropical Cloud Systems and Processes (TCSP, Halverson et al. 2007) campaign, or underflying multiple satellites during a single flight, as occurred during the NASA Goddard Space Flight Center Lidar Observation and Validation Experiment (GLOVE, Yorks et al. 2026). The large payload capacity of the ER-2 creates more opportunities for instrument synergy when designing field campaigns. For example, during the NASA Investigation of Microphysics and Precipitation of Atlantic Coast

Threatening Snowstorms (IMPACTS, McMurdie et al. 2022) field campaign (2020, 2022, 2023) targeting snowstorms over the northeastern US, the ER-2 instrument payload included four radar frequencies and a lidar, enabling unique science regarding the remote sensing of cloud and precipitation microphysics based on the differences in the coincident observations between each frequency or wavelength (e.g., Finlon et al. 2026).

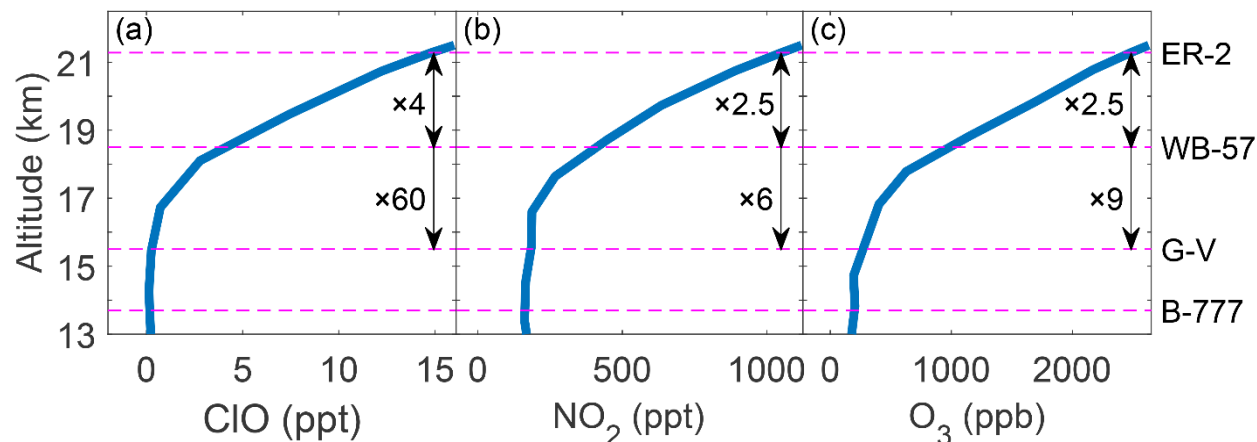


Figure 2. Typical vertical profiles of (a) ClO , (b) NO_2 , and (c) O_3 as a function of altitude for northern hemisphere midlatitudes in summertime. The maximum altitudes of the B-777 (13.7 km), G-V (15.5 km), WB-57 (18.5 km) and ER-2 (21.3 km) aircraft are indicated with dashed magenta lines. For each panel, the value of the mixing ratio at the maximum ER-2 altitude relative to the mixing ratio that would be observed at the maximum altitudes of the WB-57 and G-V, respectively, are shown next to the arrows. For example, the mixing ratio of ClO at the maximum ER-2 altitude is approximately a factor of 4 higher than at the maximum WB-57 altitude and approximately a factor of 60 higher than at the maximum G-V altitude. The data shown are representative of measurements obtained from the ER-2 in the NASA DCOTSS field campaign over the United States in summers 2021 and 2022. The ClO data shown are for daytime conditions. Figure provided by Survey Respondent David Wilmouth.

While many of the strengths of the ER-2 are inherited from the U-2 aircraft design, there are a number of strengths that are specific to the NASA ER-2. A prime example of this is the modular payload bays on the ER-2 that are not present on their U-2R counterparts. This modular design enables instruments to be easily installed or removed from the aircraft both at the start or end of a campaign as well as during the campaign, a useful feature for repairing or modifying an instrument between flights. In our survey, the ER-2 ground and air crews were repeatedly praised by the scientists and engineers as a major strength of the ER-2 program. The pilots, in particular, were noted as having a reputation for being fully invested in the mission science goals. The availability of dedicated navigators for the ER-2 operations allows missions planning to continue during flight operations, which greatly facilitates flying missions on consecutive days; this is in contrast to other aircraft where the pilots fill the role of navigators, which they cannot do while they are flying the aircraft.

4. The Challenges of the ER-2 from a Mission Science Perspective

In addition to querying the community on the strengths of the ER-2, we also asked about the challenges of using the ER-2 as an airborne research platform. The airfield requirements were frequently listed as a key challenge faced by mission science leadership in finding a viable deployment location. Key among the airfield requirements are the presence of an available hanger of sufficient size and the willingness of the airfield to host the ER-2 operations and support equipment, including the tanks of specialized fuel.

Another frequently listed challenge was the restrictive take-off and landing conditions, particularly in terms of surface winds. Table 1 lists the ER-2 airfield visibility and wind limits provided to the mission scientists during the NASA IMPACTS field campaign. In addition to the visibility and wind limits, there was also a requirement that there be no lightning within 5 miles or heavy rain over the airfield within 2 hours prior to takeoff. Furthermore, the forecasted visibility and wind must remain within limits for the duration of the planned flight to ensure the aircraft could return to base early if needed. In the event that the airfield conditions unexpectedly exceeded these limits, the ER-2 could be diverted to an alternative landing airfield, likely resulting in a major interruption to a field campaign (and potentially to airport operations) until the necessary support equipment arrives.

The uniqueness of the ER-2 also creates weaknesses as an airborne research platform. Because the ER-2, like the U-2, is so different from other aircraft, highly skilled and specialized pilots are required for the flights. These pilots must wear a pressure suit when flying the aircraft, which requires acclimatization. Between this acclimatization period and other preflight activities (such as being strapped in the aircraft), the 12-hour pilot duty day is eroded to 8-hours for flight operations, which sets the practical maximum flight length at 8 hours. Additionally, the U-2 airframes are susceptible to damage or loss in severe turbulence, and being a single-engine aircraft imparts an increased risk of loss when flying in a location where the nearest viable landing location is beyond their glide distance (approximately 250 nautical miles at 68,000 ft).

Table 1. Take-off and landing airfield condition limits for the ER-2 during the NASA IMPACTS field campaign.

	Take-off	Landing
Visibility	> 200 ft ceiling > ½ mi visibility	> 200 ft ceiling > ½ mi visibility
Winds	< 15 kt crosswind (gust) < 25 kt sustained winds < 35 kt wind gusts	< 15 kt crosswind (gust) < 35 kt wind gust

5. Conclusions

NASA's high altitude airborne assets are a vital resource for accomplishing NASA's mission. The ER-2 is capable of carrying a 1.275-ton payload of instrumentation well into the stratosphere at subsonic speeds for the duration of its 8-hour flight endurance. The WB-57 combines an even higher payload weight capacity with the option to forward deploy to alternative airfields but lacks the altitude of ER-2 or the endurance of the Global Hawk. The Global Hawk, although no longer flown in support of NASA science, had an unrivaled endurance that enabled unique mission profiles (e.g., flying multiple targets, observing continuous feature evolution over an extended time, flying over distant targets) but had the lowest payload capacity of the trio and lacked the altitude of the ER-2. Combined, this trio of high-altitude aircraft represented a versatile toolbox of airborne platforms that could address a wide variety of mission profiles. If the NASA ER-2s are retired, the WB-57Fs will be the only aircraft remaining in the toolbox for high-altitude missions, regardless of specific mission needs.

Despite the challenges that will be imposed by the retirement of the USAF U-2R fleet, we feel that retaining aircraft access to these altitudes is worthwhile. Extending ER-2 operations beyond the retirement of their USAF counterparts is not without precedence. By the time NASA acquired the first ER-2 in 1981, the NASA WB-57 fleet had already outlived their USAF counterparts by seven years, and, despite this, the WB-57 fleet still sees regular work in 2026. While the challenges that will be faced by the ER-2 program

post-U-2 retirement will be different than those faced by the WB-57 program, NASA has demonstrated prior experience with maintaining legacy airframes. Additionally, the continuation of the ER-2 program beyond USAF retirement would preserve a strategic resource: a cadre of pilots with the knowledge and skills to fly the ER-2 and U-2 aircraft. The ER-2 and U-2 are unique and challenging aircraft to fly and require pilots with specialized skills. Without the pool of pilots with the skills and knowledge to fly these aircraft, it would be difficult to restart either the ER-2 or U-2 program to meet future needs.

The ER-2 aircraft have enabled ground-breaking science over the past four decades due to their ability to collect data above most of the Earth's atmosphere and in a critical layer of the stratosphere for ozone research. The establishment of a definitive connection between the ozone hole and man-made CFCs in the late 1980s was only possible with the ER-2. The stratospheric ozone layer is critical to life on the Earth's surface. Looking forward, in-situ observations of the stratosphere will be critical to testing, evaluating, and studying climate impacts on ozone in addition to possible geo-engineering solutions to climate change.

The role of the ER-2 as a steerable, reconfigurable satellite-simulator provides the ability to obtain targeted observations quickly and inexpensively, relative to a pathfinder satellite mission which takes multiple years to develop. In this role, the ER-2 also provides a steppingstone to space for instruments with repeated flights building the technology readiness level (TRL) and reducing risks for future spaceborne applications of the instrument. Likewise, data collected by the ER-2 is critical to developing and refining techniques and algorithms for use on NASA's spaceborne missions (such as the space dust microanalysis techniques developed from the ER-2's cosmic dust collection missions and applied to the OSIRIS-REx asteroid sample return mission). In addition to its importance to developing instruments and algorithms, dealing with design requirements for flying aboard the ER-2 (e.g., temperature and vibrational considerations, aircraft safety needs, and the ability of the instrument to run unattended) provide training opportunities for instrument scientists and engineers to learn skills and attention to detail that can then be applied to spaceborne instrument development.

NASA has a limited number of high-altitude platforms available for science and the recent gear-up emergency landing of a WB-57 highlights the critical importance of each individual high-altitude platform. Reducing the number of high-altitude airborne platforms risks jeopardizing NASA's ability to conduct science and develop the technology readiness level of future spaceborne instruments.

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