National Aeronautics and Space Administration

EXPLORE

Science Mission Directorate

Airborne Science Program

2021 Annual Report

COVER IMAGES:

Front top: WB-57 as seen from ER-2 during ACCLIP / DCOTSS Intercomparison flight. Photo Credit: Tim Williams

Front center: ER-2 as seen from WB-57 during ACCLIP / DCOTSS Intercomparison flight. Photo Credit: Tom Parent

Front lower: ER-2 taking off for DCOTSS flight. Photo Credit: Carla Thomas

Back top: Four League Bay (straddling Atchafalaya and Terrebonne basins) from B-200 carrying AVIRIS-NG during Delta-X.
Photo Credit: Mark Helmlinger

Back bottom: DC-8 returns to flight. Photo Credit: Carla Thomas

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Figures and Tables

1. Leadership Comments

Bruce Tagg, Director of the Airborne Science Program.

We'd like to welcome you to another addition of the NASA Airborne Science Program Annual Report. We hope you enjoy learning about the science as well as the people and aircraft that make the science possible. We again have a unique set of science mission acronyms from MOOSE to OMG to HYPPOS, although my personal all-time favorite is still ICE AXE. Regardless of the names, it is amazing to me that we have been able to conduct over 2,400 flight hours throughout the world and across the U.S. while dealing with not one but several variants of COVID-19. Our Centers, as well as our PI's and their institutions, have stepped up health protocols and have been able to safely navigate through this. Unfortunately, despite all mitigation efforts, the virus has still caused mission impacts and affected the health of our people. Some have gotten sick and have managed to take the time needed to recuperate and get back to the science. We are grateful for this true dedication.

While we have done amazing science around the world and completed multiple investigations that you can read about, we have also had tragedy strike the program. This year, the program lost a valued friend and supporter, Dr Gail Skofronick-Jackson. She was a pleasure to work with and I was lucky enough to have been able to work closely with her in my role at Headquarters. Like all good program managers, she was always trying to get me to pay for things, in a nice way of course! She will be truly missed.

We dedicate this edition of the ASP Annual Report to Dr. Jackson and to her family and friends who are still reeling from her loss. As her passing reminds us, life is short. So please stay safe both on and off the job and hopefully you can enjoy the time you have, ignore some of the more annoying aspects of everyday life and remember what is important to you - your family and your friends.

Bruce A. Tagg
and the ASP Leadership Team
Airborne Science Program

2. Program Overview

The Airborne Science Program (ASP) is an important element of the NASA Science Mission Directorate (SMD) Earth Science Division (ESD) because of its involvement and support throughout the entire life cycle of Earth observing space missions. Aircraft modified with ports, inlets, internet (IT), and communications systems support NASA Earth Science missions by:

- Providing a platform for testing future satellite or International Space Station (ISS) instruments;
- Conducting underfligths for calibration and validation of on-orbit missions;
- Simulating future satellite mission data for algorithms development with airborne prototype instruments;
- Supporting process studies to provide high-resolution temporal and spatial measurements of complex local processes, which can be coupled to global satellite observations for a better understanding of the complete Earth system;
- Leading workforce development through hands-on science and engineering opportunities.

The program accomplishes these goals by providing support of operations of mission critical, or core aircraft; engineering for instrument mechanical, electrical, and IT integration; and onboard data systems and communications capabilities. The Program also assists NASA Principal Investigators (PIs) with access to commercial aviation services and use of non-NASA aircraft and equipment for Earth Science, as needed.

Program Structure

The Program is administered through the SMD/ESD, with oversight and close coordination from the Flight and Research and Analysis (R&A) Programs (see Figure 1). Aircraft operations and science support responsibilities are distributed among the NASA centers – Armstrong Flight Research Center (AFRC), Langley Research Center (LaRC), Wallops Flight Facility (WFF), Johnson Space Center (JSC), and Ames Research Center (ARC) – where the aircraft and support personnel are based, as shown in Figure 2.

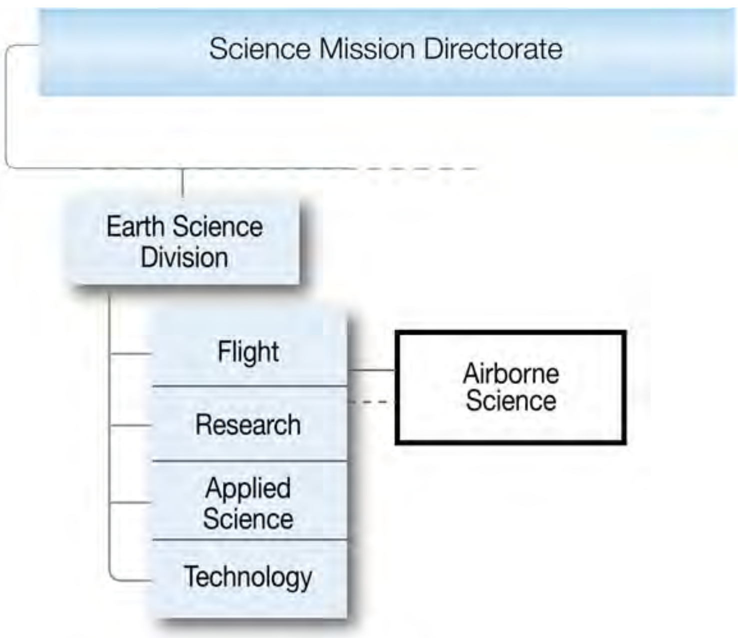


Figure 1. *Science Mission Directorate organization chart.*

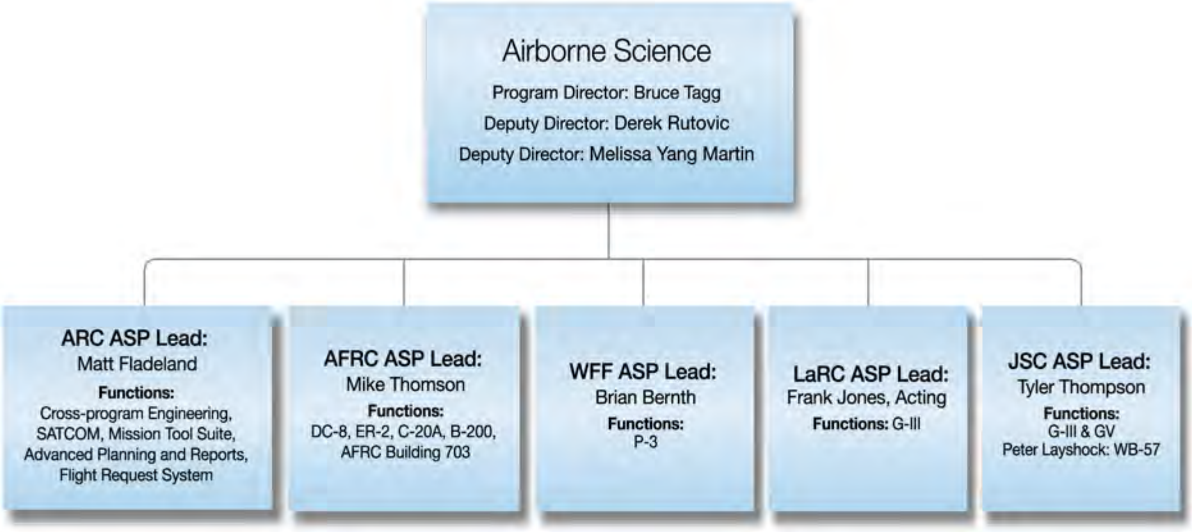


Figure 2. *Airborne Science Program organization chart.*

Flight Request System and Flight Hours

The program's Science Operations Flight Request System (SOFRS) is a web-based tool used to track and facilitate the review and approval process for airborne science activities using ASP-supported aircraft, facility instruments, ASP science support assets, or any ESD-funded activities using aircraft. To schedule use of NASA SMD platforms and instrument assets, submit a Flight Request (FR) through SOFRS (https://airbornescience.nasa.gov/sofrs).

In FY2021, 148 FRs were submitted for flight activities using at least one of the following ASP components: an ASP-supported aircraft, ESD funding, an ASP facility instrument (AVIRIS-NG, AVIRIS-C, eMAS, LVIS, MASTER, NAST-I, UAVSAR), and/or an ASP Science Support Asset (DMS, POS AV Applanix). A total of 50 FRs were completed using 28 different aircraft. Of the remaining FRs, some were deferred and the rest were canceled for a variety of reasons. The 50 completed FRs flew a total of 2424.9 flight hours. These included 1120.5 hrs for ASP-supported aircraft, 484.6 hrs for other NASA aircraft, and 819.8 hrs for non-NASA commercial aircraft.

Table 1 shows all SOFRS flight hours flown by all aircraft, including "Other (non-NASA) Aircraft," by funding source. Table 2 shows the status of all flight requests and total flight hours. Table 3 shows flight request status and total hours for the specific "Other (non-NASA) Aircraft" requested. Table 4 shows only ESD flight requests and flight hours flown by aircraft. Table 5 shows all SOFRS flight hours flown by funding source. Figure 3 shows the global reach of flight activities in 2021. Figure 4 is a histogram showing the history of total flight hours flown over the past 5 years.

*How to read Tables 1, 2, 3 and 4:

- The "Total FRs" column includes Flight Requests submitted for fiscal year FY21; these log numbers start with "21".
- The "Total FRs Approved" column includes Flight Requests that were approved but may or may not have flown during FY21.
- The "Total Partial FRs" column includes Flight Requests for which the total approved hours were not fully expended during FY21 and have been rolled over to the following year.
- The "Total FRs Completed" column includes only Flight Requests with the final status of "Completed".

The "Total Hours Flown" column includes all "Flight Hours Flown" for Flight Requests with a status of "Completed" or "Partial" for FY21.

Table 1. *NASA airborne science total hours flown by each NASA aircraft (per funding source). "Other" aircraft are identified in Table 3.*

Aircraft	NASA ESD	NASA SMD	Other NASA	Non - NASA	Not Listed	Total
Gulfstream C-20A (GIII) – AFRC	261.3	0.0	0.0	0.0	0.0	261.3
Gulfstream III – JSC	182.0	0.0	65.8	0.0	0.0	247.8
Gulfstream III – LaRC	73.8	0.0	106.6	0.0	0.0	180.4
ER-2 – AFRC	172.3	0.0	0.0	0.0	0.0	172.3
Gulfstream V – JSC	167.4	0.0	0.0	0.0	0.0	167.4
DC-8 – AFRC	72.4	0.0	0.0	0.0	0.0	72.4
P-3 Orion – WFF	0.0	0.0	0.0	0.0	0.0	0.0
B-200	303.0	0.0	0.0	0.0	0.0	303.0
HU-25A Guardian – LaRC	159.6	0.0	0.0	0.0	0.0	159.6
Cessna 206H - LaRC	10.2	0.0	11.8	0.0	0.0	22.0
WB-57 – JSC	18.9	0.0	0.0	0.0	0.0	18.9
C-23 Sherpa - WFF	0.0	0.0	0.0	0.0	0.0	0.0
SIERRA – ARC	0.0	0.0	0.0	0.0	0.0	0.0
Twin Otter – GRC	0.0	0.0	0.0	0.0	0.0	0.0
Other	807.8	0.0	9.3	0.0	2.7	819.8
TOTAL	**2228.7**	**0**	**193.5**	**0**	**2.7**	**2424.9**

Table 2. *FY21 flight request status and total hours flown by all aircraft.*

	Total FRs	Total Approved	Total Partial	Total Completed	Total Hours Flown
ASP Supported Aircraft					
DC-8 - AFRC	15	2	0	2	72.4
ER-2 - AFRC	24	9	0	3	172.3
Gulfstream C-20A (GIII) - AFRC	17	12	1	8	261.3
Gulfstream III - JSC	10	7	0	6	247.8
Gulfstream III - LaRC	7	4	0	4	180.4
Gulfstream V - JSC	4	3	0	3	167.4
P-3 Orion - WFF	12	0	0	0	0.0
Other NASA Aircraft					
B-200	8	4	0	4	303.0
C-23 Sherpa - WFF	1	0	0	0	0.0
Cessna 206H - LaRC	2	2	0	2	22.0
HU-25A Guardian - LaRC	1	1	0	1	159.6
SIERRA - ARC	3	0	0	0	0.0
Twin Otter - GRC	2	0	0	0	0.0
WB-57 - JSC	3	1	0	1	18.9
Other (see Table 3)	39	16	0	16	819.8
TOTAL	**148**	**61**	**1**	**50**	**2424.9**

Table 3. *FY21 flight request status and total hours flown by other (non-NASA) aircraft.*

	Total FRs	Total Approved	Total Partial	Total Completed	Total Hours Flown
Other Aircraft					
A90 - Dynamic Aviation	3	2	0	2	34.1
Alphajet	1	0	0	0	0.0
B-200 - Dynamic Aviation	18	9	0	9	523.8
DC-3	2	1	0	1	154.9
Twin Otter CIRPAS	1	0	0	0	0.0
Twin Otter International	6	2	0	2	41.6
Dynamic Aviation, King Air, via Quantum Spatial	1	0	0	0	0
Helicopter	1	0	0	0	0
ISRO King Air	1	0	0	0	0.0
Robinson R-44	1	0	0	0	0.0
Scientific Aviation Mooney	1	0	0	0	0.0
SkyFish M6	1	0	0	0	0.0
UK Twin Otter	1	1	0	1	62.7
Vanilla-003	1	1	0	1	2.7
TOTAL	**39**	**16**	**0**	**16**	**819.8**

Table 4. *Summary of ESD-funded flight request status and flight hours flown by aircraft.*

	Total FRs	Total Approved	Total Partial	Total Completed	Total Hours Flown
ASP Supported Aircraft					
DC-8 - AFRC	10	1	0	1	72.4
ER-2 - AFRC	13	5	0	3	172.3
Gulfstream C-20A (GIII) - AFRC	16	12	1	8	261.3
Gulfstream III - JSC	7	6	0	5	182.0
Gulfstream III - LaRC	4	2	0	2	73.8
Gulfstream V - JSC	3	3	0	3	167.4
P-3 Orion - WFF	10	0	0	0	0.0
Other NASA Aircraft					
B-200	7	4	0	4	303.0
C-23 Sherpa - WFF	1	0	0	0	0.0
Cessna 206H - LaRC	1	1	0	1	10.2
HU-25A Guardian - LaRC	1	1	0	1	159.6
SIERRA - ARC	1	0	0	0	0.0
Twin Otter - GRC	2	0	0	0	0.0
WB-57 - JSC	3	1	0	1	18.9
Other (see Table 3)	31	11	0	11	807.8
TOTAL	**110**	**47**	**1**	**40**	**2228.7**

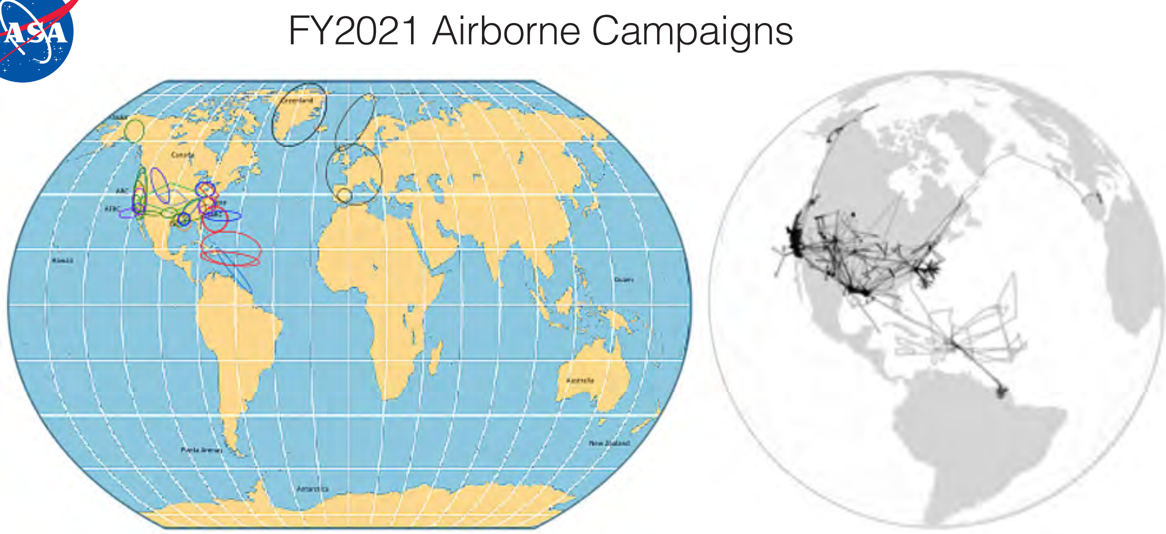


Figure 3. *Locations and flight tracks of FY21 ASP airborne campaigns.*

Figure 4. *ASP annual flight hours from FY17 through FY21.*

Table 5. *All flight hours flown by funding source.*

Fiscal Year	ESD	SMD (Non-ESD)**	Other NASA	Non-NASA	Funding Sources Not Listed in FR	Total Funded Flight Hours
2017	4484.4	85.9	280.1	194.1	0.0	5044.3
2018	3125.8	6.4	451.5	103.6	1.2	3688.5
2019	2415.1	0.0	586.6	60.6	7.5	3069.8
2020	1614.0	0.0	129.9	0.0	0.0	1743.9
2021	2228.7	0.0	193.5	0.0	2.7	2424.9

3. Science

Major Mission Highlights

Despite continuing safety and logistics challenges introduced by a global pandemic, in FY21 ASP conducted over 2400 flight operation hours in support of Earth science process studies, instrument flight-testing, and support for Earth Science space missions in all phases from definition to validation. Four of the five Earth Venture Suborbital-3 (EVS-3) missions were able to carry out flight activities. The final EVS-2 mission, OMG, completed Greenland measurements

Table 6. *FY21 major science missions.*

Mission		Flight Hours	Location	Aircraft
EVS	ACTIVATE	339.6	Atlantic Coast	Falcon, UC12-B
	Delta-X	266.9	Mississippi River Delta	G-III (radar), B-200 (2)
	OMG	154.9	Greenland	DC-3
	DCOTSS	97.5	Mid-America (Kansas base)	ER-2
	S-MODE*	82.8	California	B-200 (A)
R&A	AVIRIS-NG Europe	179.5	Europe (multiple locations)	B-200
	SHARC	136.8	Australia	G-III (radar); G-III (L)
	SnowEx	134.8	Colorado	G-III (radar), B-200
	SLAP LIAISE	98.0	Virginia, Spain	B-200 (L)
	Joint NASA/ISRO	94.2	CONUS, Alaska	G-III (radar)
	TRACER-AQ	93.3	Houston, TX area	GV
	HyTES Europe	80.3	UK, Sweden	British Twin Otter
	Western Diversity Time Series	74.8	California	ER-2
	CPEX-AW	72.4	Caribbean (St. Croix base)	DC-8
	LVIS/GEDI	59.2	From JSC	GV
	MOOSE	54.7	Lake Michigan	G-III (L)
	G-LiHT	34.1	Eastern Forests	A90
	UAVSAR (all combined flights)	148.3	CONUS, Alaska	G-III (radar)

in 2021. Three NASA instrument teams – AVIRIS-NG, HyTES, and SLAP – participated in three separate European missions. Table 6 shows flight hours for the largest missions.

Earth Venture Suborbital

Earth System Science Pathfinder (ESSP) Earth Venture Suborbital (EVS) projects are flagship-equivalent, $15-30M, 5-yr efforts that focus on the most compelling science questions for which aircraft measurements are critical to resolving uncertainties. ACTIVATE, DCOTSS, Delta-X, and S-MODE all carried out flight missions in 2021. IMPACTS postponed its second flight season to early 2022.

Aerosol Cloud Meteorolgy Interactions Over the Western Atlantic Experiment

PI – Armin Sorooshian, University of Arizona
Program – Earth Venture Suborbital-3
Aircraft – HU-25A, UC-12B
Payload Instruments – CVI, AC3, RSP, HSRL-2

The Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment (ACTIVATE; https://activate.larc.nasa.gov/) conducted its third and fourth flight campaigns in January-March and May-June of 2021. A total of 15 joint flights were conducted in the winter campaign with the HU-25A and UC-12B, while 32 joint flights were conducted between May-June 2021. In total, after two years of flying, four and seven joint flights have been coordinated with overpasses of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) platform, respectively. The winter 2021 flights continued to build data statistics for cold air outbreak events off the East Coast that give rise to shallow cumulus clouds that current models simu-

The Earth Venture Suborbital program element solicits science proposals for multi-year, Principal Investigator-led, suborbital, campaign-based investigations to advance Earth system science objectives to better understand the current state of the Earth and predict future change. The Earth System Science Pathfinder (ESSP) Program is responsible for management, direction, and implementation of the selected opportunities.

ESSP, as part of ESD, supports a variety of innovative Earth science research projects that study atmospheric composition, weather, carbon cycle and ecosystems, water and energy cycle, climate variability and change, and Earth surface and interior.

ESD and the Earth science community are the ESSP Program's immediate stakeholders. ESD provides the ESSP Program with its operating budget, programmatic guidelines, and scientific goals and objectives.

The overall objective of the EVS program element is to substantially advance Earth system science and NASA's Earth science goals through innovative science investigations involving sustained aircraft and/or other suborbital data acquisition campaigns. This overall objective can be met in several ways, including but not limited to:

- acquiring measurements that address weaknesses in current Earth system models, leading to improvement in modeling capabilities and accuracy;
- producing data sets that identify and characterize important phenomena and/or detecting and characterizing changes in the Earth system; and/or
- making measurements that contribute to the scientific goals of multiple Earth Science focus areas and/or disciplinary programs.

The program has routine funding calls and approximately five investigations are selected every four years.

- The selected investigations are specialized campaigns utilizing a variety of suborbital assets to gather science data. The investigations may contain airborne as well as ground and/or water in situ or remote measuring instruments.
- So far there have been three rounds of EVS selections (EVS-1, EVS-2, EVS-3). Solicitation for EVS-4 is expected in 2023.
- EVS-4 provides opportunities for two different classes of investigations, differentiated by their overall cost constraint: "Large" investigations with an overall NASA cost constraint of $30 million (M) over the lifetime of the investigation, and "Small" investigations with an overall NASA lifetime cost constraints of $15M.
- The Airborne Science Program supports EVS by providing access to NASA aircraft and support at subsidized rates.

Figure 5. *ACTIVATE team members Yonghoon Choi, Luke Ziemba, and Edward Winstead consulting after a research flight in front of the HU-25A.* ***Photo Credit:*** *Johnathan Hair, LaRC*

late poorly. Flights examined conditions upwind of the cloud systems and along the transport path of these clouds as they transition from overcast areas to more scattered cloud fields. The summer 2021 campaign included two meticulously designed "process study" flights, whereby developing cloud clusters were extensively characterized with numerous stacked level legs by the HU-25A below, in, and above the clouds. Simultaneously, the UC-12B conducted a "wheel and spoke" pattern centered around the cloud system, with multiple dropsondes launched above and on the periphery of the cloud cluster, along with remote sensing transects to characterize the cloud and aerosol profiles. Data from both planes will be used to characterize the range of cloud types observed on such flight days, with a focus on understanding the processes that drive shallow cumulus organization.

DELTA-X

PI – Marc Simard, JPL
Program – Earth Venture Suborbital-3
Aircraft – G-III (Radar), B-200 (2)
Payload Instruments – UAVSAR (L-band), AirSWOT, AVIRIS-NG

Delta-X is an EVS-3 mission that seeks to predict the fate of different parts of the Mississippi River delta in the face of sea level rise. Delta-X uses a combination of airborne remote sensing and in situ measurements to calibrate models that simulate the processes controlling soil elevation in deltas, namely the deposition of sediment and the production of organic matter by plants.

Delta-X successfully conducted its only two airborne and field campaigns to study how water and sediment is exchanged (the 'X' in Delta-X) during different conditions of river discharge and vegetation phenological stage. NASA's airborne science instruments AirSWOT, UAVSAR, and AVIRIS-NG collected data, while four field teams collected measurements across the coastal wetlands. Delta-X kicked off its spring campaign in southern Louisiana on March 26, 2021, coinciding with the high annual discharge period of the Mississippi River. The Fall campaign occurred between August 20 and September 25, 2021, corresponding to a period of low river discharge, when herbaceous plants reached their peak biomass. Delta-X went through a brief hiatus for Hurricane Ida, which made landfall just east of the Delta-X 2021 study area.

The three instruments were needed to simultaneously capture sediment transport, vegetation conditions, and water flow path and extent. AirSWOT is used to measure the water surface elevation and slope in open river channels, while UAVSAR measures water level changes in vegetated areas, and AVIRIS-NG serves to characterize vegetation structure and suspended sediment concentrations in the networks of rivers and channels. Field teams accessed field sites from boats and by hiking across the wetland to collect information on vegetation; water level, flow, and quality; sediment deposition rates, distribution, and grain size; and channel bathymetry. The airborne and field data will be combined to calibrate and validate numerical models of sediment capture and organic matter production to evaluate how hydrological and ecological processes contribute to land gain or land loss in the Mississippi River delta.

The Delta-X study area encompasses two adjacent basins that are largely disconnected, the Atchafalaya and Terrebonne basins. These basins offer a unique opportunity to understand how different parts of a delta evolve with sea level rise: while the Atchafalaya basin gains land, the Terrebonne is losing land at an alarming rate. Repeated airborne remote sensing and in situ measurements were made at different phases of the tidal cycle to document the tide-driven water propagation with the wetlands – only with airborne sensors can we capture these rapid processes. For more information and to obtain the data: https://deltax.jpl.nasa.gov/

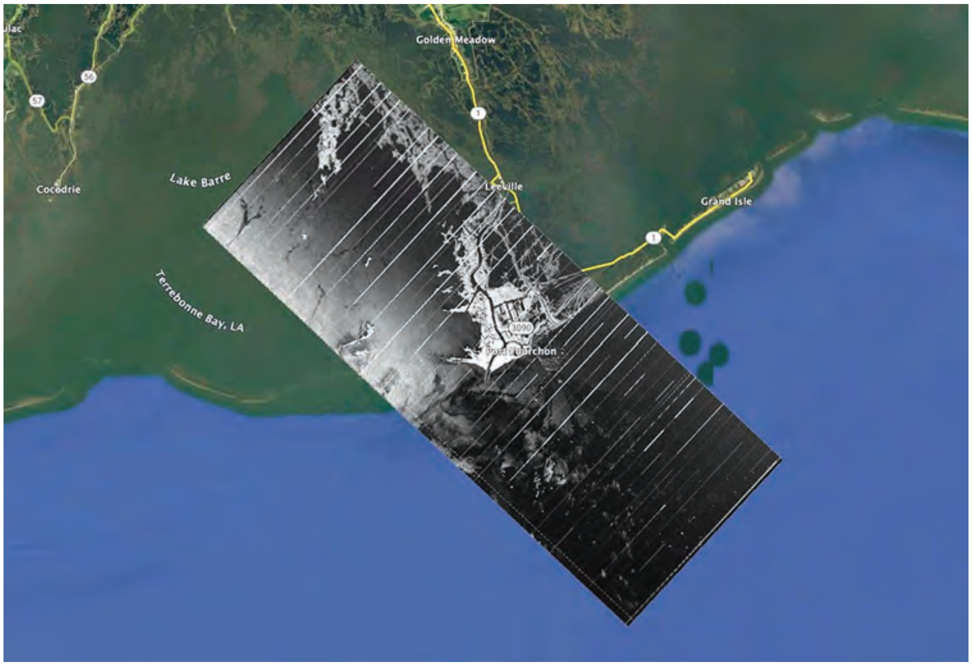


Figure 6. *UAVSAR quick-look image during Delta-X.*

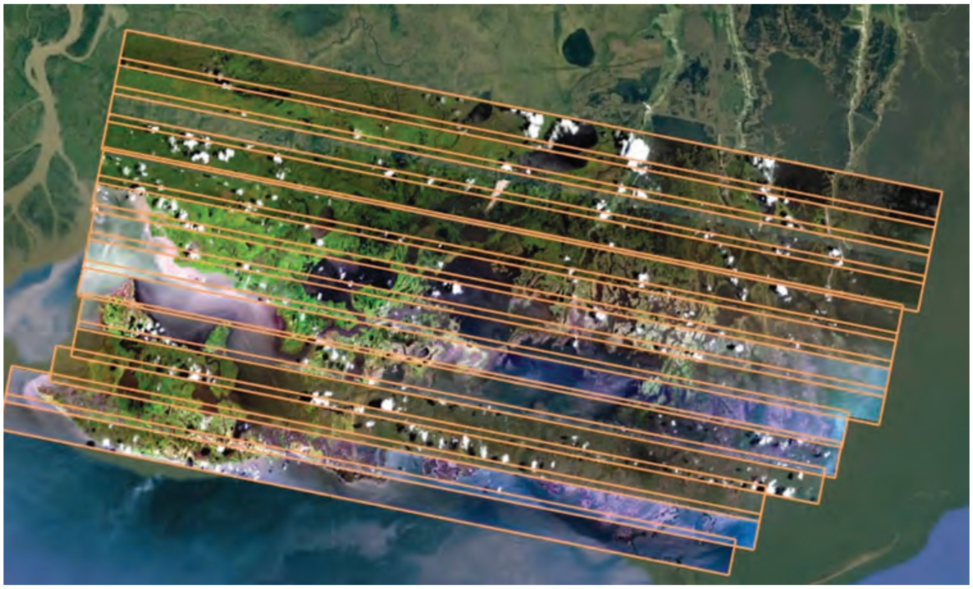


Figure 7. *AVIRIS-NG vegetation lines and images during Delta-X.*

Oceans Melting Greenland (OMG)

PI – Josh Willis, JPL
Program – Earth Venture Suborbital-2
Aircraft – Basler DC-3
Payload – AXCTDs

On September 16, 2021, OMG completed its sixth and final airborne survey of the oceans surrounding Greenland. OMG's mission was to observe changes in ocean conditions and glacier changes around all of Greenland to answer the question: "how much are the oceans melting Greenland's ice from below?" With more than 60 peer reviewed scientific publications to date (https://omg.jpl.nasa.gov/portal/publications), OMG has shown that the oceans play a major role in controlling the behavior of Greenland's glaciers, and predicting ocean warming will be a critical part of projecting future ice loss and sea level rise. With 25 feet of potential sea level rise locked away in Greenland's ice, OMG has taken a major step toward better predictions of sea level rise, which will affect hundreds of millions of people over the next century.

OMG's ocean survey was carried out in late summer each year since 2016. It was designed to measure the temperature and extent of sub-surface Atlantic water on the continental shelves around Greenland, which is warmer and saltier than surface water and eats away at the glaciers. During most years, approximately 250 temperature and salinity profiles were collected. For 2021, during OMG's six-week deployment 335 one-time profiling sensors were launched. In Figure 8 yellow dots show planned drops, green dots show completed drops and purple dots show the locations were profiling floats were deployed. In addition, the team deployed six surface drifters to measure surface temperature and currents and nine profiling floats, which will continue to collect profiles on the shelf even after the mission ends. During the last few years, OMG has deployed several such floats and found they last on the shelf and continue to collect data through the winter, when the water is covered by sea ice. Thus, in addition to meeting all its baseline science requirements, OMG demonstrated that this float technology is a viable tool for monitoring the deep water on the shelf that is so important for predicting glacier behavior.

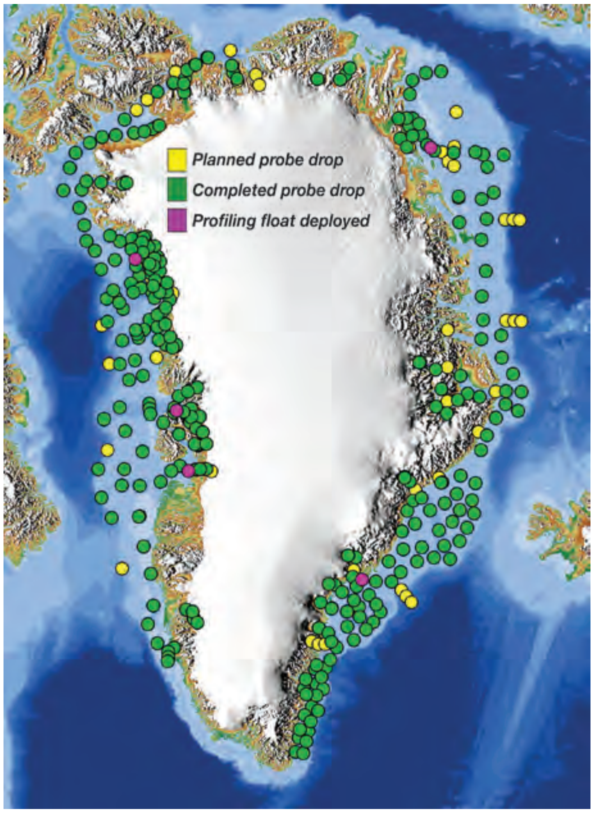


Figure 8. *2021 AXCTD survey of the oceans around Greenland.*

Finally, OMG carried out a major outreach campaign during the 2021 deployment. The crew spent the last week of the campaign flying from Nuuk, the capital of Greenland. During this time, OMG flew five flights with officials from the U.S. State Department, NASA Headquarters, and the Greenland Government, in addition to several local scientists, and a Greenlandic schoolteacher and student. More than a dozen public talks were given, reaching hundreds of students. Four U.S. media outlets (ABC News, Univision, the Post and Courier, and Getty Images) also participated in flights and covered the mission. On September 16, OMG Principal Investigator Josh Willis dropped the last probe of the mission on a flight with Principal Deputy Assistant Secretary from the U.S. Department of State, Jonathan Moore, Greenland's Minister of Foreign Affairs, Pele Broberg, and the head of the Climate Research Centre at the Greenland Institute of Natural Resources, Mie Winding. These flights helped build goodwill between NASA and Greenland's government, its science institutions, and its people, which will hopefully serve them all for years to come.

Figure 9. *OMG Principal Investigator Josh Willis with Mie Winding (left), OMG Project Manager Ian McCubbin (background), Pele Broberg, and Jonathan Moore (right and far right). Inset: Josh Willis deploys the final probe for the OMG mission.* ***Photo Credit:*** *Josh Willis, JPL*

Figure 10. *Kenn Borek Air crew member Gerald Cirtwill prepares to launch an APEX float during the 2021 OMG Ocean Survey.* ***Photo credit:*** *Josh Willis, JPL*

Figure 11. *A tour of the Basler aircraft with local school children in Nuuk, Greenland during OMG.* ***Photo Credit:*** *Josh Willis, JPL*

Dynamics and Chemistry of the Summer Stratosphere (DCOTSS)

PIs – Kenneth Bowman, Texas A&M University; Frank Keutsch, Harvard University
Program – Earth Venture Suborbital-3
Aircraft – ER-2
Payload Instruments – CAFE, CANOE, AWAS, HAL, ROZE, HWV, HUPCRS, MMS, PALMS, POPS, UCATS, WI-ICOS

The main goal of the DCOTSS project is to study the lower stratosphere. During the summer, strong convective storms over North America overshoot the tropopause into the lower stratosphere. These storms carry water and pollutants from the troposphere into the normally very dry stratosphere, where they can have a significant impact on radiative and chemical processes, potentially including stratospheric ozone. Figure 12, a photo taken from the International Space Station, shows one of these storms with an anvil, which is typically near the tropopause level; an overshooting top; and a plume of cirrus (ice) clouds injected into the stratosphere by the overshooting top. Overshooting tops can reach many kilometers above the tropopause into the stratosphere.

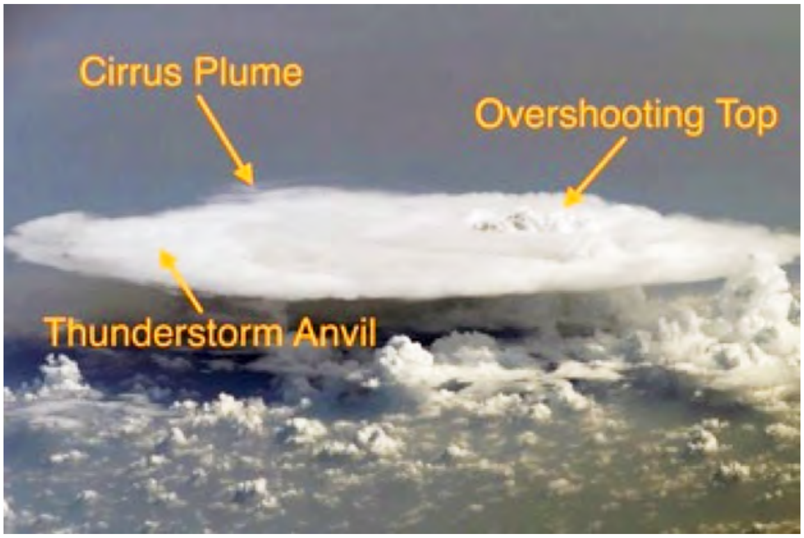


Figure 12. *View of an overshooting convective storm, as seen from the International Space Station.*

Material transported from the troposphere to the stratosphere by these storms may be trapped by the atmospheric circulation in the lower stratosphere. During the Summer, the circulation over North America is dominated by a large high-pressure system known as the North American Monsoon Anticyclone (NAMA).

DCOTSS flies on the high-altitude ER-2 to measure the composition of these convective plumes and determine their effects on the chemistry and composition of the stratosphere. ER-2 flights for DCOTSS were based in Salina, Kansas, which offers an ideal mid-America location for sampling convective plumes in the stratosphere. The ER-2 carried an extensive suite of instruments to measure trace gases and aerosol properties and can operate at altitudes as high as 70,000 feet. Commercial airliners, by comparison, typically fly at around 35,000 feet.

DCOTSS, an EVS-3 project, successfully concluded its first science deployment in July/August 2021. This achievement is of particular significance due to delays related to the COVID-19 pandemic. DCOTSS originally planned to have three deployments, with the first one scheduled for mid-Summer 2020. Pandemic delays forced the team to restructure from three deployments to two longer deployments. This change will allow the DCOTSS participants adequate time dedicated to post-deployment science data analysis.

On August 17, during the last science flight, the DCOTSS project had the opportunity to do a coordinated flight with the NASA WB-57. The WB-57 was supporting the integration and test flight efforts of the ACCLIP project at NASA JSC. A subset of the instruments deployed (AWAS, MMS, and PALMS) are common to both projects. This coordinated flight was a unique opportunity to conduct instrument intercomparison, and the data collected are already leading to significant observations. During the 2021 Summer DCOTSS deployment, the ER-2 project flew 16 flights for a total of 97.5 hours, of which 83 hours (12 flights) were science flights.

Figure 13. *ER-2 Flight tracks during the Summer 2021 DCOTSS campaign.*

Sub-Mesoscale Ocean Dynamics Experiment (S-MODE)

PI – Tom Farrar, Woods Hole Oceanic Institute (WHOI)
Program – Earth Venture Suborbital-3
Aircraft – B-200, Twin Otter
Payload Instruments – DopplerScatt, MOSES, MASS

The S-MODE investigation is examining small-scale ocean eddies and the impact they have on the exchange of heat between the ocean and the atmosphere, and ultimately how that exchange contributes to climate change. This type of data has been difficult to collect in the past, as ocean currents can move too quickly and be too large to be studied by a research vessel and in situ assets alone, and yet can often be too small to be observed via airborne instrumentation surveys. The S-MODE investigation aims to study ocean submesoscales, utilizing shipborne surveys, robotic surface vehicles, and remote sensing airborne observations in a Goldilocks approach to help researchers understand them in greater detail.

After postponing in the Spring of 2020 due to the COVID-19 pandemic, S-MODE successfully completed a short spring Test Campaign in May 2021 and a Pilot Campaign in the Fall of 2021. For approximately two weeks in May, test flights were conducted using two of S-MODE's research aircraft: a B-200 from AFRC and a commercial Twin Otter. The B-200 was equipped with JPL's DopplerScatt instrument that measured currents and winds near the ocean surface with radar. The B-200 was also equipped with UCLA's Multiscale Observing System of the Ocean Surface (MOSES) instrument that measured sea surface temperature. The Twin Otter was equipped with an instrument from the Scripps Institution of Oceanography (SIO), the Modular Aerial Sensing System (MASS),

Figure 14. *On board AFRC B-200, Hector Torres Gutierrez (JPL DopplerScatt operator) and Delphine Hypolite (UCLA MOSES operator) in action during an S-MODE science flight.* ***Photo Credit:*** *Scott Howe, AFRC*

that measured the height of ocean waves. Flying from Palmdale, CA, the research aircraft were accompanied by Wave Gliders, which were deployed in the ocean and measured several ocean conditions, including the speed and direction of the ocean eddies. The May campaign was an excellent way to intercompare the measurements from DopplerScatt, MASS, MOSES, and Wave Gliders, and to better understand the data and increase confidence in the measurements for the Fall campaign.

Then, for approximately three weeks in Fall 2021, the S-MODE platforms operated from ARC in the experimental region about 200 miles off the coast of San Francisco, CA. The same airborne platforms, carrying the same instruments, were joined by in situ assets (Wave Gliders, NAVO Gliders, Saildrones) and the Oregon State University (OSU) Research Vessel Oceanus. The B-200 completed a total of twelve science flights. The Twin Otter completed a total of ten science flights. Oceanus measurements included over a thousand profiles of upper-ocean temperature, salinity, oxygen, and chlorophyll fluorescence. The ship also launched Wave Gliders (robotic surface vehicles that collected data at various levels below the surface) and surface drifters. The research party aboard the Oceanus consisted of scientists from Woods Hole Oceanographic Institution (WHOI), the University of Washington, OSU, Caltech, and the University of Rhode Island. Saildrones and Naval Oceanographic Office (NAVO) Gliders were also operated in the experimental region, remotely piloted by their respective institutions.

Within the S-MODE study region, there were several features (ocean fronts and filaments), and an unusual atmospheric river event that the team observed and measured over the weeks of the deployment. Figure 16 depicts one day of operations; the platform's positions and planned operating paths changed daily. The mission planning and control center operations were handled remotely, highlighting the team's adaptability to organize the daily sampling plans. Coordinating aircraft, robotic surface vehicles, and a research

Figure 15. *S-MODE team ready to depart for Science Flight 9.*
Photo Credit: *Erin Czech, ARC*

vessel was a challenge, and the Pilot program was a great opportunity to fine tune this critical element.

The research team met virtually, planning and re-planning deployments and fine tuning the experimental plan. The team's hard work is being rewarded with an exciting data set collected during the Pilot campaign, generating enthusiasm amongst the team for long awaited intercomparison of measurement and data analysis. The team is looking forward to the longer deployment planned for the Fall of 2022, including the addition of the PRISM instrument flying on the LaRC G-III.

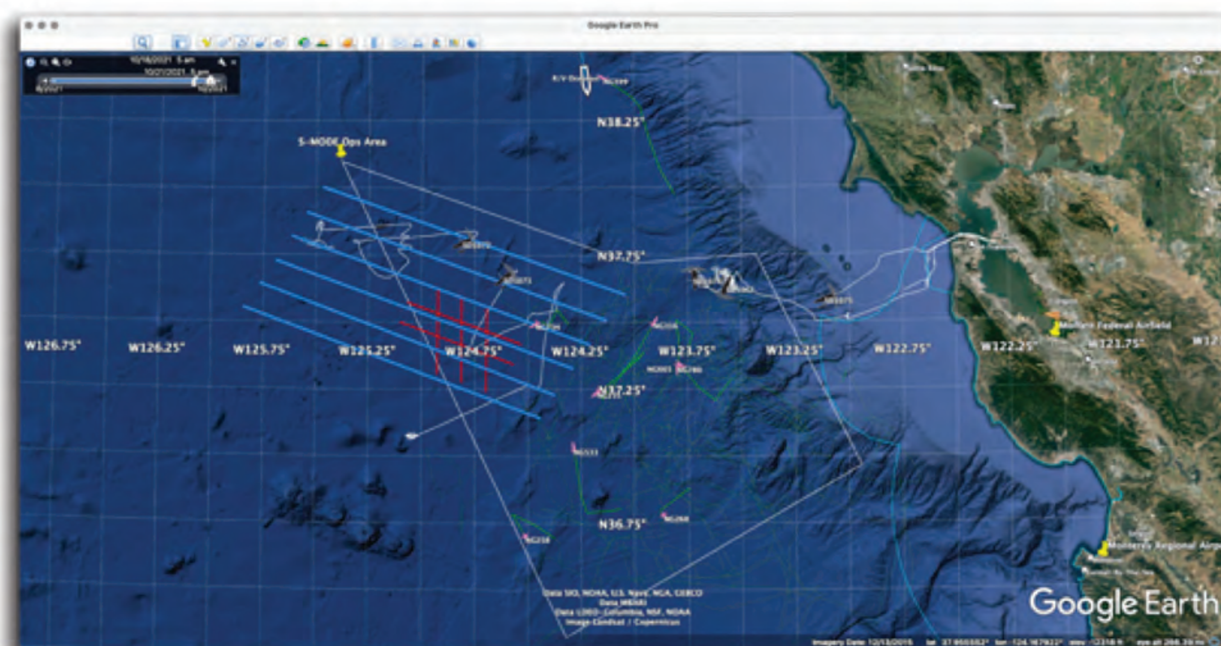


Figure 16. *View of S-MODE Operations Area taken at the beginning of the Pilot campaign. R/V Oceanus, Saildrones, and NAVO Gliders are pictured. Flight plans for the B-200 (blue lines) and the Twin Otter (red lines) are also displayed.*
Figure Credit: *Ben Greenwood, WHOI*

Convective Processes Experiment – Aerosols and Wind (CPEX-AW)

Mission Scientists – Shuyi Chen, U. Wash.; Ed Zipser, U. Utah
Program – Weather and Atmospheric Dynamics
Aircraft – DC-8
Payload Instruments – DAWN, APR-3, HALO, HAMSR, AIRO, Dropsondes

The CPEX project is a joint effort between NASA and the European Space Agency (ESA). It has a primary goal of conducting post-launch calibration and validation activities for the Atmospheric Dynamics Mission – Aeolus (ADM-AEOLUS) Earth observation wind Lidar satellite. In addition, CPEX-AW studies the dynamics and microphysics related to the Saharan Air Layer, African Easterly Waves and Jets, Tropical Easterly Jet, and deep convection in the InterTropical Convergence Zone (ITCZ).

These dynamic weather studies, especially those including dropsondes, required close coordination with multiple organizations. NOAA and its hurricane division (CARCAH), along with the U.S. Air Force, were part of daily aircraft coordination discussions and two groups launched soundings from remote locations.

The deployment took place in St. Croix, U.S. Virgin Islands, August 19 - September 14, 2021. Over 120 researchers, including graduate students and postdocs, participated in CPEX-AW in St. Croix, Puerto Rico, and remotely. There were seven research flights on the DC-8 as part of this joint NASA-ESA Aeolus calibration/validation effort over the tropical Atlantic Ocean to address the science objectives of studying convective cloud systems, aerosols associated with the Saharan Air Layer, and tropospheric winds. CPEX completed a total of 48.5 hours of science flights and 17.1 hours of transit, testing, and maintenance flights (Figure 17).

The DC-8 was equipped with DAWN, HALO, APR-3, HAMSR, AIRO, and dropsondes and underflew six Aeolus overpasses for a total underflight distance of 5,836 km. A total of 130 dropsondes were deployed.

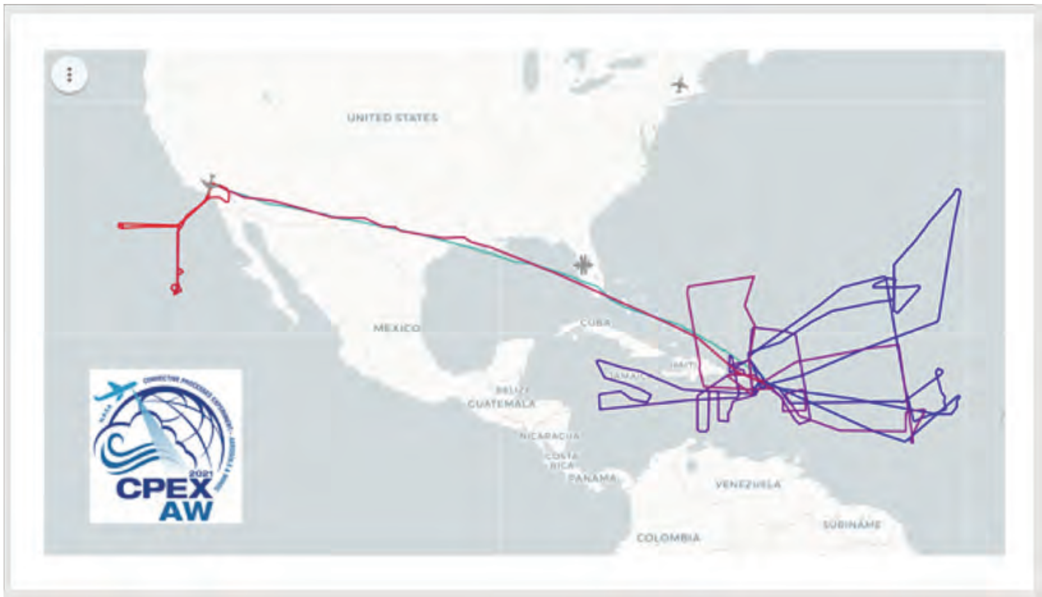


Figure 17. *All DC-8 flight lines during CPEX-AW, including science, transit, and testing/maintenance flights.*

Figure 18. *CPEX-AW team in St. Croix, U.S. Virgin Islands.* ***Photo Credit:*** *Judy Alfter*

Two groups from University of Utah and University of Oklahoma launched soundings from the North Coast of St. Croix and the west coast of Puerto Rico (Mayaguez). They "repurposed" the originally stated scientific objectives of the sounding program in view of the relocation of the DC-8 base of operations from the East Atlantic to West Atlantic. In St. Croix, 72 soundings were launched between August 19 and September 14, with good sampling of the diurnal cycle. In Puerto Rico, 31 soundings were launched between August 24 and September 14. These captured significant island effect with typical afternoon west winds.

Figure 19. *Science stations fill the DC-8 during CPEX-AW.* ***Photo Credit:*** *Aaron Piña*

A total of 15 flights were originally planned for CPEX-AW. However, multiple events, including an aircraft depressurization and a tragic accident leading to the death of the program scientist, Dr. Gail Skofronick-Jackson, led to ending the CPEX-AW 2021 campaign early. The six completed flights will yield a wealth of scientific data. Plans to continue deployment in 2022 from Cape Verde are underway.

Figure 20. *Gail Skofronick-Jackson, Ed Zipser, and Shuyi Chen during a preflight meeting.* ***Photo Credit:*** *CPEX team*

TRacking Aerosol Convection ExpeRiment – Air Quality (TRACER-AQ)

PI – Laura Judd, LaRC
Program – Atmospheric Composition
Aircraft – GV
Payload Instruments – GCAS, HSRL-2

Supported by ESD's R&A and Applied Sciences programs, the TRACER-AQ mission leveraged activities associated with the Department of Energy's TRacking Aerosol Convection ExpeRiment (TRACER) over the Houston, TX region. The mission included air quality ground-based assets (e.g., TOLNET ozone lidars and Pandora spectrometers), as well as outfitting the JSC GV with an air quality remote sensing payload to collect data as a proxy for the NASA Tropospheric Emission: Monitoring of Pollution (TEMPO) mission. TEMPO will be the first geostationary air quality satellite mission sampling multiple times daily over greater North America following launch in early 2023.

The JSC GV payload included the GeoCAPE Airborne Simulator (GCAS) and High Spectral Resolution Lidar-2 (HSRL-2), which were installed in both nadir ports of the aircraft for the first time. From September 1-27, these instruments were flown on 11 science flights, 89.2 hours and over 38,000 miles traveled, to repeatedly map air quality over the Houston, TX region. The GV's endurance is optimal for all-day repeated sampling of air quality over a targeted area. This allows the capture of the diurnal evolution of emissions and insight into how they interact meteorologically and chemically, impacting air quality. Research flight durations ranged from 5 to 9.6 hours.

During the first ten science flights, this payload collected 27 maps of the spatial distribution of ozone, ozone precursors (NO_2 + HCHO), and aerosol characteristics over the Houston,

Figure 21. *TRACER-AQ measurement strategy graphic.* ***Figure Credit:*** *Tim Marvel, LaRC*

TX region, in collaboration with the Texas Commission on Environmental Quality. The eleventh science flight took place over the Gulf of Mexico in collaboration with the Bureau of Ocean Energy Management to collect data over offshore platforms for emissions sampling. Flights were episodic due to the requirements of cloud-free skies throughout most daylight hours. The bulk of the science flights were during two multi-day air quality events (each four days in duration) from September 8-11 and 23-26, with a mid-September break due to the influence of Hurricane Nicholas and its remnants impacting cloud cover over Houston. This is the first time that NO_2 and HCHO observations from GCAS have been collected coincidently with ozone measurements from HSRL-2, creating the most comprehensive TEMPO-proxy dataset to date.

In continuance of past Houston air quality studies (the last one being DISCOVER-AQ in 2013), and in preparation for the upcoming TEMPO mission, the TRACER-AQ mission's goals included researching connections between ozone photochemistry and meteorology in Houston, TX, with a focus over adjacent bodies of water. The aircraft was able to sample in these regions, which are unmonitored by surface networks and infrequently by boat. The multi-perspective observations collected from ground and airborne instruments provide a comprehensive dataset for evaluating air quality models, as well as the utility of satellite-based remote sensing through validation of Sentinel-5P TROPOMI and proxy-datasets for TEMPO. These datasets are also being used to update findings about pollution inequality within the city, which disproportionately impacts low-income communities of color.

Highlights include, but are not limited to, top-down views of spatial patterns of NO_2, ozone, and HCHO from morning through afternoon, including observing emissions from ships and industry in the Houston Ship Channel and the greater Houston metropolitan area. The mission captured high ozone observations from multiple perspectives over the water in Galveston Bay and the Gulf of Mexico. Preliminary modeling efforts link the physics and chemistry to observed datasets in the region. TRACER-AQ science team members are from LaRC, GSFC, University of Houston, Baylor University, St. Edwards University, TCEQ, Virginia Tech, University of Virginia, and the DOE TRACER team.

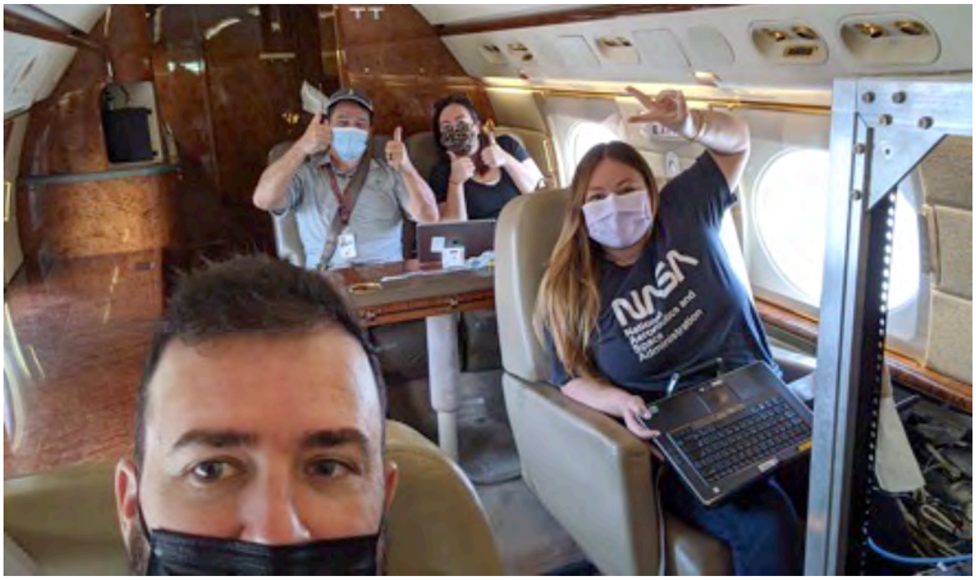


Figure 22. *Scientists on the GV for TRACER-AQ: Taylor Shingler, Jayne Boehmler, Dave Harper, and Laura Judd.*
Photo Credit:
Taylor Shingler, LaRC

SnowEx

PI – Hans-Peter Marshall, University of Boise
Program – Water and Energy Cycle
Aircraft – G-III, Twin Otter
Payload Instruments – UAVSAR, AVIRIS-NG

NASA's SnowEx campaign is a multiyear effort using a variety of techniques to study snow characteristics. SnowEx is learning valuable information about how snow properties change by terrain and over time, as well as investigating the tools, datasets, and techniques NASA will need to observe and measure snow properties from space. Current satellite missions easily measure how much of the land is covered by snow. But no single satellite currently in orbit contains an instrument or collection of instruments designed to measure snow water equivalent (SWE) and/or the snow characteristics that may be used to calculate it.

In early 2021, SnowEx teams took snow measurements at six sites across the Western U. S., on the ground and with drones and airplanes flying overhead. This information helps scientists determine how much water the winter snowpack holds, which is crucial for managing water resources for drinking, agriculture, hydropower, flood forecasting, drought and wildfire management, and more. In addition to studying snow, SnowEx researchers are also evaluating how accurately various techniques can measure snow in different environments. In the future, NASA hopes to launch a satellite dedicated to studying snow – and the water it stores – from space, to understand how changes in the snowpack affect droughts, wildfires, and more. One of the main goals of the multi-year SnowEx campaign is figuring out which remote sensing instruments may be best suited for the job. Measurements from these instruments are compared with comprehensive ground measurements made by the SnowEx team.

For 2021, the science team had three major goals: conduct a time series of L-band Interferometric Synthetic Aperture Radar (InSAR) observations in diverse snow conditions, measure the

Figure 23. *Gabrielle Antonioli (Boise State) measures the snowpack to compare with remotely sensed measurements.* ***Photo Credit:*** *HP Marshall*

reflectivity (albedo) of the snow surface, and study snow distribution in a prairie landscape.

The JSC G-III aircraft, carrying the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) flew ten sorties over the sites in Colorado, Utah, Idaho, and Montana from mid-January until the end of March, for a total of nearly 100 hours. (UAVSAR is an L-band InSAR instrument that SnowEx uses to measure changes in the mass of the snowpack.) The snowpack's mass can change drastically from one UAVSAR flight to the next if a snowstorm deposits more snow or if it melts or sublimes. Snow may also be redistributed by high winds. The SnowEx team is determining how well the UAVSAR sensor can detect these changes in the snow's mass because a similar sensor will fly on the upcoming NISAR space mission. Researchers also measured snow albedo from the air using the Airborne Visible/Infrared Imaging Spectrometer Next Generation (AVIRIS-NG). On a contracted aircraft, AVIRIS-NG flew 37.5 hours. Comparing the airborne and complementary ground measurements will help the scientists identify how different factors contribute to the snow albedo.

Scanning L-band Active Passive (SLAP)/ Land surface Interactions with the Atmosphere over the Iberian Semi-arid Environment (LIAISE)

PI – Ed Kin, GSFC
Program – Water and Energy Cycle
Aircraft – B-200 (L)
Payload Instruments – SLAP

Soil moisture is the important control on Land-Atmosphere exchange of water, energy, and carbon. Future soil moisture satellite observations (a "continuity" measurement named in the 2017 Earth science Decadal Survey), as well as soil moisture-related applications, will operate at spatial scales finer than the 10-40 km achievable by current systems, such as NASA's SMAP and ESA's SMOS soil moisture satellites. The upcoming joint NASA-India NISAR mission is an example of a future mission planning soil moisture products at the scale of individual farm fields (100s of meters). Such radar missions will always be constrained by radar's fundamental limitations when it comes to noise and soil moisture accuracy. It is therefore essential to obtain lower-noise, higher-accuracy, truth soil moisture datasets at similar resolutions for validation and algorithm development purposes. Such measurements are obtainable from passive microwave sensors, like the Scanning L-band Active Passive (SLAP) sensor, using the well-understood technique of passive microwave radiometry at L-band, which is the basis for both SMAP and SMOS. SLAP is an airborne SMAP simulator developed at NASA's Goddard Space Flight Center (GSFC).

A summer 2021 European airborne field campaign, the Land surface Interactions with the Atmosphere over the Iberian Semi-arid Environment (LIAISE) campaign, presented an opportunity to explore passive soil moisture sensing with footprints as small as 100 x 200 m, contributing a key measurement to LIAISE and at a higher level, enhancing NASA's long-running collaboration with ESA and European scientific colleagues. Such SLAP data provides detailed insight into water/energy/carbon exchanges. These are important advances for further exploitation of SMAP for weather and climate science. Furthermore, the outcome of the LIAISE campaign with SLAP will better inform planning and investments for the Surface Topography and Vegetation (STV) mission and any planetary boundary layer (PBL) missions.

SLAP, as its name suggests, makes both passive and active microwave measurements. The passive radiometer at 1.4 GHz is fully polarimet-

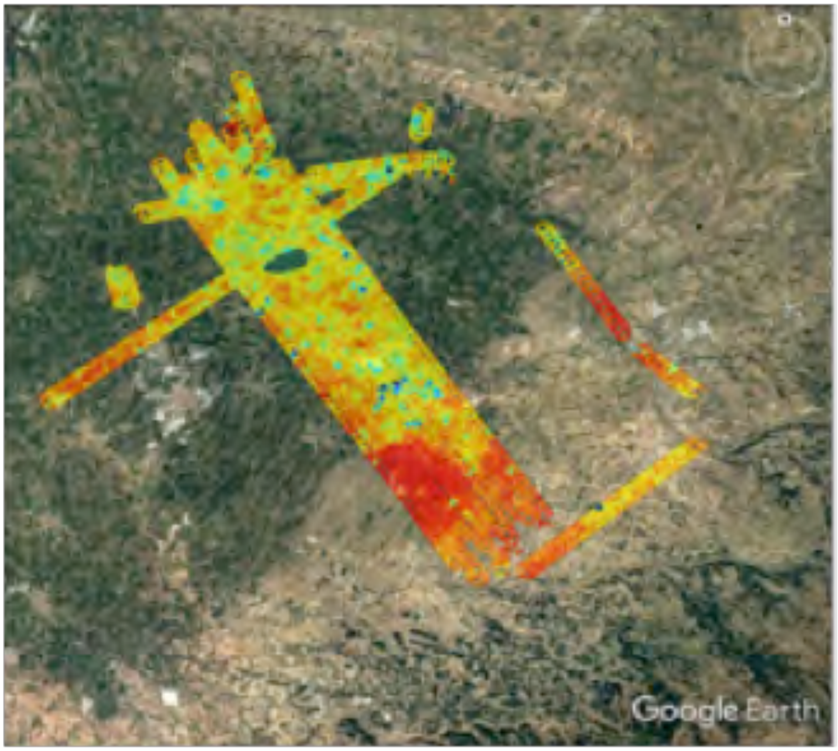


Figure 24. *SLAP soil moisture data overlaid on a 40x40km Google Earth background image.*

ric (4-Stokes) and contains a functional copy of SMAP's digital backend, enabling the detection of radio-frequency interference (RFI). The active scatterometer at 1.2 GHz is quad-polarized and shares one antenna with the radiometer. The majority of the LIAISE science flights, based out of Valencia, Spain, were at 1000 ft AGL, where the radiometer half-power footprint size is slightly less than 100 x 200 m. Two flights were at the radar minimum operating altitude of 2500 ft AGL, where its footprint size is approximately 220 x 470 m, and the radiometer footprints are 10% smaller. A key feature of SLAP is its thin packaging—only 23 cm high—enabling operation on relatively small aircraft. Since 2013, SLAP has been flying on NASA LaRC's B200 and UC-12B aircraft.

The 40 x 40 km image in Figure 24 is approximately the size of one satellite passive microwave footprint from SMAP. The individual SLAP footprints are 100 x 200m. Two days after a rain event, uneven drying appears as blue/green (wet) and red/orange (dry) locations. The wetter areas are within an irrigated agricultural region (dark area in background image), and the drier areas are mainly in the surrounding unirrigated region (light colored portions of background image).

Planning and executing an international campaign during a global pandemic presented several interesting challenges, but excellent teamwork among Langley, Goddard, HQ, embassies, Forward Operating Bases (FBOs), and logistics departments, made it possible. When SLAP is installed in the B-200, altitude is limited to approximately 11,500 ft. Therefore, the transatlantic transits of the B-200 aircraft were flown at higher altitude without SLAP. SLAP upload and download were performed in Shannon, Ireland, with the transits to/from Spain at the lower altitude.
A total of nine science flights were flown over irrigated and non-irrigated areas, as well as on dry and wet days, spanning exactly the conditions needed for LIAISE. The team's flexibility allowed

Figure 25. *SLAP team members from GSFC and LaRC in Spain, July 2021.* ***Photo Credit:*** *SLAP team*

day-to-day flight plans to be adapted to cover an ESA soil moisture validation site near Valencia on three days and a forest fire area near Barcelona on two days.

HyTES Europe

PI – Simon Hook, JPL
Program – ESD R&A
Aircraft – ER-2, Twin Otter (CAS), Twin Otter (BAS)
Payload Instruments – HyTES

HyTES FY21 flight activities included test flights prior to a major campaign in Europe to make methane measurements. For the initial test flights, HyTES was included with the WDTS payload on the ER-2. One flight with good HyTES data was achieved.

In further preparation for the European Campaign, a short checkout campaign was performed on a Twin Otter aircraft from Twin Otter International Ltd. (TOIL). The TOIL aircraft was very similar to the aircraft that the British Antarctic Survey (BAS) provided for the Europe campaign. The checkout was required since the HyTES detector array was upgraded to a more sensitive technology in early 2021. The 17.5 flight-hour campaign, covering targets in Colorado, Arizona, and California, provided a successful full-system checkout and validation of detector alignment and calibration.

The 2021 European Campaign was originally planned to include participation in a large air and ground campaign in Spain, but Spanish and U.K. COVID-19 restrictions precluded U.K. and U.S. participation there. Fortunately, travel to Sweden became possible in time for participation in a methane detection campaign based out of Kiruna in September.

The European Campaign consisted of installation on a BAS Twin Otter at Duxford Airfield, near Cambridge, England, followed by flights over an instrumented agricultural research facility in Rothamsted, England. One of the main objectives

Figure 26. *Location of HyTES sites in England.*

of the U.K. flights was to study the effects of different viewing angles on the observations. Flight lines were planned with large overlap between short lines so that each pixel on the ground would be observed from a variety of angles. Other U.K. targets included pig farms and urban areas. A total of ten science sorties were flown in the U.K., totaling 23.91 hours. Cloudy weather was the main limiting factor in the U.K. HyTES and the two instruments (Fenix VSWIR spectrometer and Phase-1 context camera) provided by King's College London (KCL) all required clear skies for proper performance.

The Sweden portion of the campaign was a methane observation campaign called Monitoring of Atmospheric composition and Greenhouse gases through multi-Instruments Campaigns (MAGIC) 2021. MAGIC 2021 consisted of three aircraft, balloons, and several ground teams. The aircraft were an ATR42 flown by SAFIRE from France, a Cessna Grand Caravan flown by DLR from Germany, and the BAS Twin Otter with HyTES and the two KCL instruments. The three aircraft shared a large hangar called Arena Arctica at the Kiruna Airport. The main objective was to detect and map methane and other greenhouse gases in areas that had shown elevated gas levels in satellite observations.

The target lines were generally long and covered a combination of lakes, wetlands, forest, and tundra. HyTES detected methane from natural sources in several locations. The DLR Cessna flew over the same locations later and also detected elevated methane with its in situ instruments. The large amount of flight data is still being analyzed. A total of eight science sorties were flown from Kiruna, Sweden, totaling 22.57 hours. The transits between Duxford and Kiruna consisted of five sorties and 16.25 hours, for a grand total of 62.73 flight hours. ESA provided the Twin Otter aircraft and all flight-related expenses.

Michigan-Ontario Ozone Source Experiment (MOOSE)

PI – Laura Judd, GSFC
Programs – Atmospheric Composition
Aircraft – G-III (L)

Led by the Michigan Department of Environment, Great Lakes, and Energy, the Michigan-Ontario Ozone Source Experiment (MOOSE) is a multi-agency study aiming to assess strategies for lowering ozone pollution in the border region of southeast Michigan and western Ontario, Canada. The 2021 component of this study included the use of mobile laboratories, drones, and a suite of ground-based measurements observing trace gases. The goal was quantifying and characterizing emissions of ozone precursors in the region. To support this study from above, the Tropospheric Composition program supported flights on the LaRC G-III with two atmospheric composition instruments from GSFC: the Geo-CAPE Airborne Simulator (GCAS) and the Cloud Physics Lidar (CPL). This is the first time these instruments have flown on this platform, which had the endurance to base flights from LaRC, transiting to the Detroit region each flight day and performing two sorties with a midday fuel in Battle Creek Michigan, before transiting back each flight day by late afternoon. The aircraft payload observed the spatial and temporal patterns of trace gases, like nitrogen dioxide (NO_2), formaldehyde, and aerosols. These measurements provide a high-resolution top-down view that will be used to evaluate chemical transport models and provide characterization of satellite column-based measurements in comparison to surface-based observations.

From June 5-24, 2021, 16 maps of data were collected over the study region during six flight days, with ozone air quality conditions ranging from clean to unhealthy for sensitive groups. The preliminary GCAS data show that the highest NO_2 column densities are attributed to isolated point sources grouped in three main regions. Due to rainy and cloudy conditions during the

Figure 27. *Matt Kowalewski integrates the GCAS instrument onto LaRC G-III aircraft for MOOSE.* ***Photo Credit:*** *David C. Bowman, NASA*

final week of the study planned for the MOOSE domain, one final flight on June 29th was moved to sampling an ozone event along the east coast of the U.S. There, the aircraft team was able to map NYC/Long Island Sound, Baltimore, MD/ Washington DC, and the Hopewell, VA area in a single flight. Total flight hours for the mission accumulated to 54.7 over 7 days.

The MOOSE science team includes participation from the Michigan Department of Environment, Great Lakes, and Energy, the U.S. EPA, Ontario Ministry of Environment, Conservation, and Parks, Environmental and Climate Change Canada, LaRC, GSFC, Aerodyne, University of Michigan, and other academic institutions.

Figure 28. *The LaRC G-III during a midday pit stop in Battle Creek, Michigan.* ***Photo Credit:*** *Laura Judd, NASA*

Asian summer monsoon Chemical and Climate Impact Project (ACCLIP) Test Flights

PIs – Paul Newman, GSFC; Laura Pan, NCAR
Program – Atmospheric Composition
Aircraft – NASA WB-57F, NSF/NCAR G-V
Payload Instruments – NASA WB-57F: 2DS, AWAS, BBR, Chi-WIS, CPI, COLD2, COMA, DLH, FCDP, ISAF, LIF-NO/SO2, MMS, PALMS, ROSCOE, SP2, UASO3, UTLS-AMP

ACCLIP is an airborne field project, jointly sponsored by NASA and NSF, with contributions from NOAA and NRL. The campaign is scheduled to take place in July-August 2022, operating from Osan AB, Republic of Korea. ACCLIP has a primary goal to investigate the impacts of Asian emissions on global chemistry and climate via the linkage of Asian Summer Monsoon (ASM) convection and associated large-scale dynamics. The related science is detailed in the section on Upcoming Campaigns (page 40).

In preparation for ACCLIP, the team conducted three test flights from Ellington Field, TX. These flight tests have proved incredibly valuable for the mission. Many issues and problems were identified and fixed, with the fixes verified in subsequent flights. These tests were a key milestone in ACCLIP's readiness for the 2022 campaign.

During the successful third and final test flight, history was made when two high altitude aircraft (ER-2 and WB-57) flew an inter-comparison flight at 55,000 ft. The aircraft flew in formation for over an hour, with no issues reported.

Figure 29. *Left: ACCLIP UTLS and DLH instrument teams (Nowak, Ziemba, Brown, Diskin). Right: ACCLIP pre-flight brief.*
Photo Credit: *ACCLIP team*

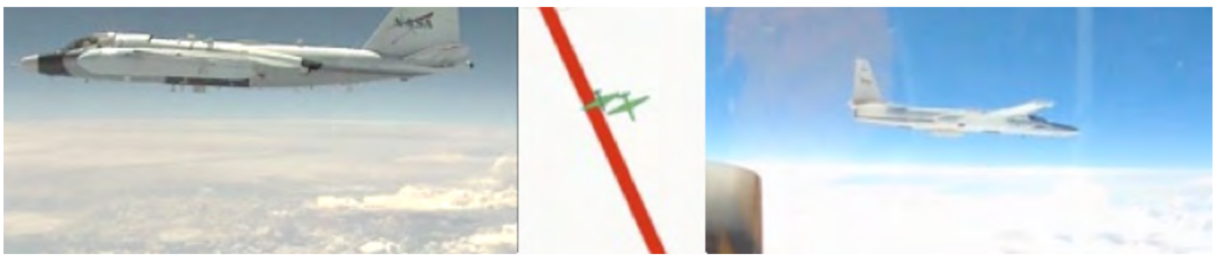


Figure 30. *Intercomparison flight of WB-57 (left) and ER-2 (right) at 55,000 ft during overlap of DCOTSS mission and ACCLIP test flights. Insert (middle) shows the aircraft in formation during the flight.*

Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR)

PI – Yunling Lou, JPL
Programs –Water and Energy Cycle, Earth Surface and Interior
Aircraft – G-III (JSC), C20-A (AFRC)

During FY21, UAVSAR supported eleven Flight Requests, seven Principal Investigators, and one Rapid Response Event. The AFRC G-III conducted 53 flights and acquired 582 data lines for a total of 261 hours. The JSC G-III conducted 28 flights and acquired 208 data lines for a total of 182 hours. Together, these two platforms collected 790 lines that served a broad range of disciplines. As shown in Figure 31, 153 data lines were acquired with the ASAR instrument, 93 with P-band, and 544 with L-band.

Delta-X was the largest deployment in 2021 and was supported by AFRC and JSC. UAVSAR's L-band radar observed water level change during different tidal states in support of the Delta-X mission to study relative sea level rise in the Mississippi Delta. Hurricane Ida hit the Gulf Coast in September as the crew was positioned to fly over the Mississippi River Delta. During this time, the UAVSAR team worked in collaboration with NASA's Disasters Program to derive flood maps for impacted sites in Louisiana.

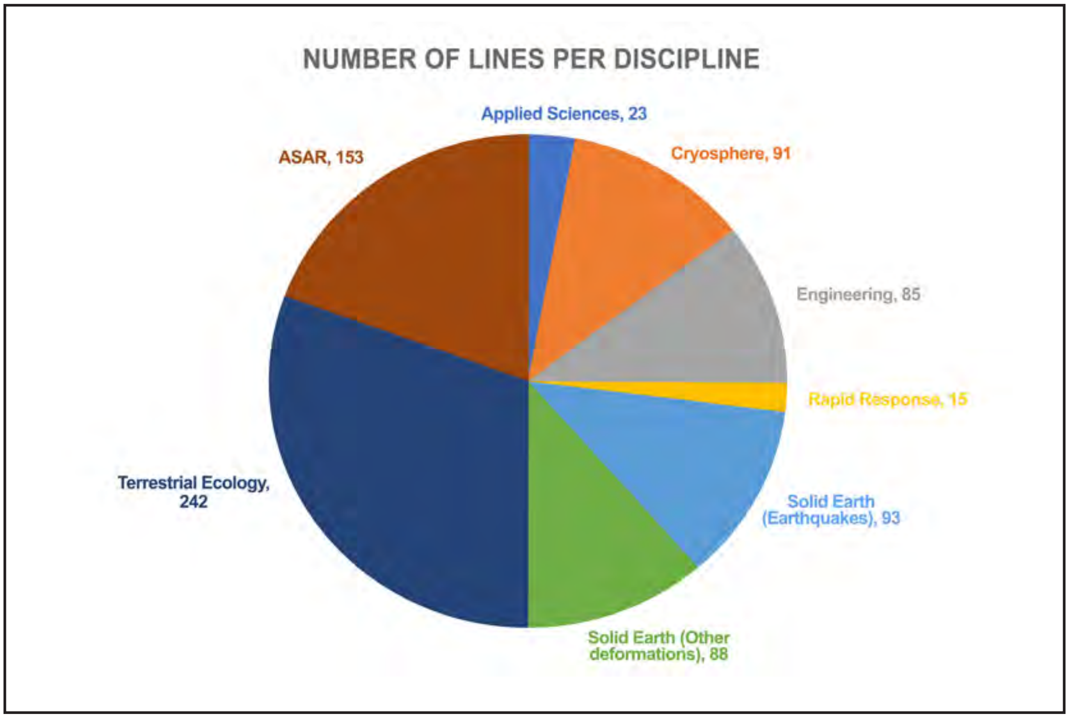


Figure 31. *UAVSAR data lines acquired in FY21, by discipline.*

A month-long campaign was conducted with ASAR, an instrument built and operated by the Indian Space Research Organization (ISRO). ASAR's dual-wavelength (L + S) instrument acquired sample data to support NISAR science algorithm development and calibration/validation activities. Planned to launch in 2023, NISAR is a joint mission between NASA and ISRO. The ASAR campaign was supported by AFRC and took place between June and July 2021.

For a second year, 2021 marked UAVSAR involvement in SnowEx, a multi-instrument air and in situ campaign that surveyed sites in the

Figure 32. *Crew members Elizabeth Ruth and Timothy Williams inside G-III during ASAR flights.* ***Photo Credit:*** *D. Austerberry*

Western U.S. to develop and test new methodologies for retrieving snow volume and water content. Measurements collected by university researchers provide essential ground truthing data to assess new remote sensing methodologies.

UAVSAR was also employed to quantify the impact of recent fire events in California. The L-band instrument was used to survey an active fire (Caldor) and post-fire recovery zone (Bobcat). In May 2021, the L-band instrument imaged an oil slick off the coast of Santa Barbara. In collaboration with the U.S. Coast Guard, the research team deployed a boat and drones to accurately locate the oil slick. Results are being used to develop and test methodologies for mapping oil spills with SAR.

Local campaigns in California continue to support earthquake and landslide studies. UAVSAR L-band repeat observations were used to estimate the 3D motion of 134 slow-moving landslides in the northern California Coast Ranges. In addition, P-band images were collected in Fall 2020/Spring 2021 to study landslides in the Pacific Northwest. The increased penetration of the P-band signal can help overcome limitations in areas of high vegetation density to reveal the behavior of deep-seated landslides.

Advancing the data processing capabilities of the UAVSAR program, the team has developed P-band repeat-pass InSAR products to observe subsurface deformation caused by the thawing of permafrost in the arctic region and deep-seated landslides in the heavily vegetated Pacific Northwest. The team has also developed simulated NISAR products by modifying UAVSAR's L-band data to emulate NISAR data characteristics to help users test their algorithms and get a sense of the quality of future NISAR products. So far, over 400 simulated NISAR products for 70 flight lines over a variety of scientific disciplines have been delivered.

UAVSAR Next Generation Update

The team has developed a modernization plan to refresh the UAVSAR instrument suite while continuing to support science and technology demonstrations, as well as EVS missions. Capability prioritization is guided by community input collected at the UAVSAR NextGen workshop held in May 2020 and includes:

- Simultaneous P/L-band operation
- Longer range, especially for Antarctic imaging aboard the GV
- S-band Polarimetric InSAR capability
- L-band single-pass interferometry
- Ability to support bistatic/multi-static operation

These new capabilities will enable the SAR program to support Surface Topography (STV) and Vegetation incubation activities and Surface Deformation and Change (SDC) mission studies in the upcoming decade.

ASP Support to ESD Satellites and International Space Station Missions

In addition to EVS, the primary stakeholders in ASP are Earth Science space flight missions, including satellite missions and missions on the International Space Station (ISS). The Program provides platforms to collect data for algorithm development prior to launch, testing instrument concepts for satellite/ISS payloads or airborne simulators, and providing data for calibration or validation of satellite algorithms, measurements, or observations once in orbit. In FY21, ASP provided support to a number of operational Earth Science space missions (Table 7). Collecting data in support of GEDI, both versions of the LVIS instrument flew on the GV aircraft.

Several FY21 airborne process missions also collected data valuable to future missions. Airborne campaigns are providing image data and instrument performance data to support TEMPO, scheduled to launch in 2023, and NISAR, scheduled to launch in 2023. Future missions include Surface Biology and Geology (SBG), which is supported by years of data now identified as the Western Diversity Time Series (WDTS). Data collection using AVIRIS-NG in Europe in 2021 supported SBG and the European mission Copernicus Hyperspectral Imaging Mission for the Environment (CHIME).

Table 7. *Space missions supported by aircraft campaigns in FY21.*

Airborne Mission	Space Mission Supported	Flight Hours	Location	Aircraft
ACTIVATE	Calipso	339.6	Atlantic Coast	UC-12B, HU-25A
AVIRIS-NG Europe	CHIME, SBG	179.5	Europe	B-200
UAVSAR Combined Missions	NISAR	148.3	CONUS, Alaska	G-III
SNOWEX	ICESat-2	134.8	Colorado	G-III, B-200
SLAP LIAISE	SMAP	98.0	Spain	B-200 (L)
TRACER-AQ	TEMPO, Sentinel	93.3	Houston area	GV
Western Diversity Time Series	SBG	74.8	California	ER-2
CPEX-AW	GPM, Calipso	72.4	Caribbean	DC-8
S-MODE	SWOT	82.8	Pacific Coast	B-200, TO
LVIS / GEDI	GEDI	59.2	From JSC	GV
MOOSE	TEMPO	54.7	Lake Michigan	GV
G-LiHT	Landsat 8	34.1	Eastern CONUS	A90
MURI	Landsat 8	31.2	California	Twin Otter
QUAKES imager	STV	14.9	CA to TX	GV
EPA THEROS	TEMPO	4.5	LaRC	Cessna 206H

AVIRIS-NG Europe

PI – Robert Green, JPL
Program – Water and Energy Cycle, Carbon Cycle and Ecosystems
Aircraft – ER-2
Payload Instruments – AVIRIS-NG

A joint NASA and ESA airborne imaging spectrometer campaign in support of future space missions took place in Europe to advance cooperation and harmonization of algorithms and products from future global imaging spectrometer missions. The effort was intended to support the future SBG mission and the candidate European CHIME mission. The NASA AVIRIS-NG deployed to Europe during May to July for this campaign, which flew a total of 179.5 flight hours. The numerous imaging locations are shown in Figure 33.

All measurements were rapidly calibrated, atmospherically corrected, and made available to NASA and ESA investigators to: 1) further test and evaluate new state-of-the-art science algorithms, including atmospheric correction; 2) grow international science collaboration in support of ESA CHIME and NASA SBG; 3) test/demonstrate calibration, validation, and uncertainty quantification approaches; 4) collect strategic cross-comparison under-flights of the current space missions, including DESIS, PRISMA, and Sentinels. For NASA, this campaign benefits the ongoing SBG Designated Observable activity.

Figure 33. *AVIRIS-NG data acquisition locations in Europe.*

Western Diversity Time Series (WDTS)

PI – Robert Green, JPL
Program – Water and Energy Cycle, Carbon Cycle and Ecosystems
Aircraft – ER-2
Payload Instruments – AVIRIS-classic MASTER, HyTES

The Western Diversity Time Series (WDTS) campaign continues to extend a decade-long time series of measurements by NASA airborne instruments AVIRIS-Classic, MASTER, and HyTES, covering five large-area blocks and a long transect in the Western United States. This combination of visible to shortwave infrared (VSWIR) imaging spectroscopy and multispectral thermal infrared (TIR) imagery has captured the diversity of the encompassed environments, as well as the changes in ecosystems across a range of elevational gradients through pre-drought, drought, and now severe drought. The instruments fly on the ER-2 high-flying aircraft. The FY2021 campaign flew a total of 72.6 hrs.

The resulting dataset is a unique asset for research and applications communities seeking to understand the influence of a changing water cycle on a wide variety of natural and human-dominated ecosystems in a large and biologically diverse region, which is also characterized by very high levels of cultural and economic diversity. Continuing this one-of-a-kind time series is well justified for scientific research, with more than 100 articles published. In addition, the size of the large-area blocks imaged by the multi-year dataset and the combination of VSWIR imaging spectroscopy and multispectral TIR imagery make these time series data valuable for the SBG Designated Observable mission.

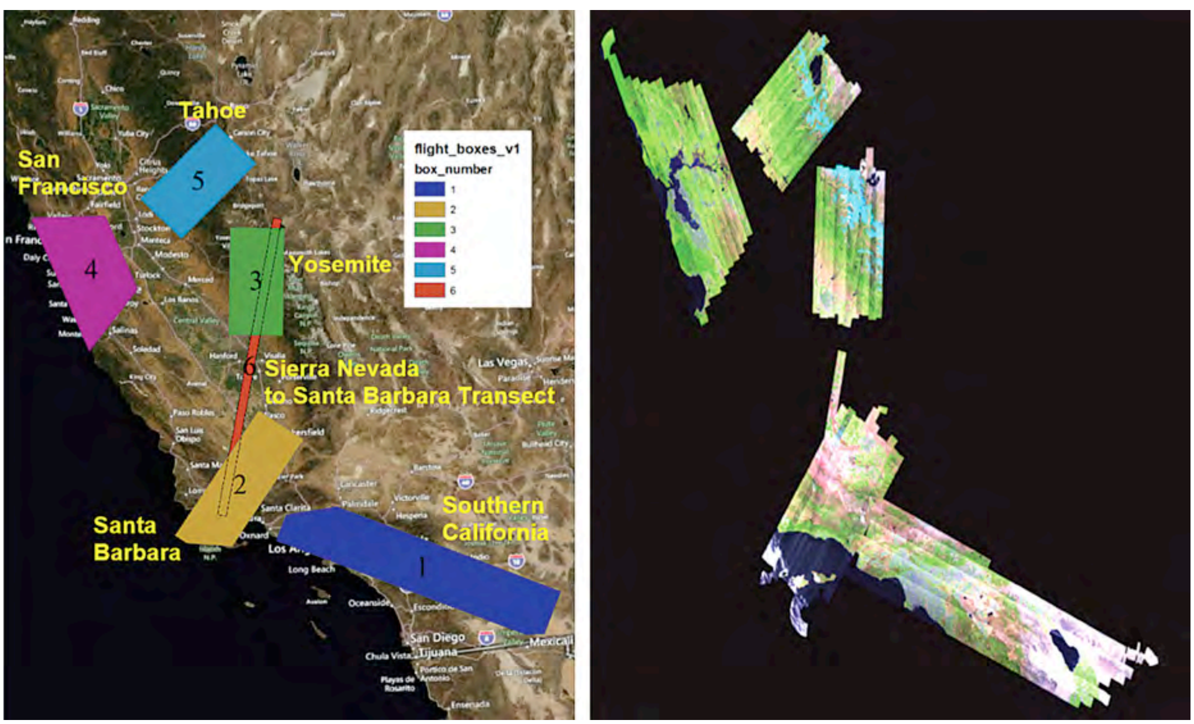


Figure 34. *ER-2 continues flights of California boxes for the Western States Diversity Time Series.*

LVIS / GEDI

PI – Bryan Blair and Michelle Hofton, GSFC
Program – Water and Energy Cycle
Aircraft – GV
Payload Instruments – LVIS

In July and August 2021, the Land, Vegetation, and Ice Sensor (LVIS) Lidar Facility instrument flew a campaign supporting calibration and validation of NASA's Global Ecosystem Dynamics Investigation (GEDI). GEDI is a multi-beam lidar system, operating on the International Space Station, that measures surface topography, and canopy height and structure. GEDI data are used for global vegetation structure mapping for carbon studies and monitoring ecosystem structure. Two LVIS lidars (the original PI version and the new facility sensor), along with high-resolution camera sensors, were mounted onboard the JSC GV for high-altitude data collections in French Guiana and the Eastern U.S.

Operations began in the U.S., with science data collected on the transit from Houston, TX to Baltimore, MD and on a science out-and-back flight from Baltimore. The team then relocated to San Juan, Puerto Rico for a total of four flights over French Guiana before returning to Baltimore to conduct two remaining science flights. The primary set of flight objectives was to undertake country-scale sampling of GEDI ground tracks for calibration and validation of algorithms over dense South American forests in the Guiana Shield. The Guiana Shield is a dramatic geological formation on the north coast of South America and one of the most bio-diverse locations on Earth. A secondary objective focused on sampling GEDI ground tracks in the U.S. for a geolocation assessment to better understand the impact of degraded attitude determination periods on data quality.

The flight lines flown during the deployment are shown in the left portion of Figure 35. Flight operations over French Guiana were dependent on daily cloud conditions, with data collection timed to begin as soon as possible after sunrise and continuing until cloud conditions prevented further useful collection. In the U.S., a local mapping sortie was flown over the Coweeta, North Carolina, Long Term Ecological Research (LTER) area, along with transects over the Smithsonian Environmental Research Center (SERC) area in Maryland and the Harvard Forest LTER area. Approximately 10,000 km of GEDI ground tracks were overflown during the mission, including tracks that were then sampled by GEDI within a week of the LVIS data collection.

LVIS provides full waveform lidar sampling across a 2-km wide swath and captures the detailed vertical structure in each laser footprint. Data were collected with footprint diameters ranging from 5 to 25 m. The two LVIS lidar sensors were operated concurrently during the mission, producing collocated data sets using different measurement parameters and providing data sets that can be used in lidar sensor design studies on vegetation penetration as a function of footprint diameter and spacing.

As a bonus, the LVIS team enjoyed the company of NASA Associate Administrator for the Science Mission Directorate, Thomas Zurbuchen, PhD, on two science flights over French Guiana, where he was able to see LVIS in operation and how the team collects important and unique data sets in challenging cloud conditions.

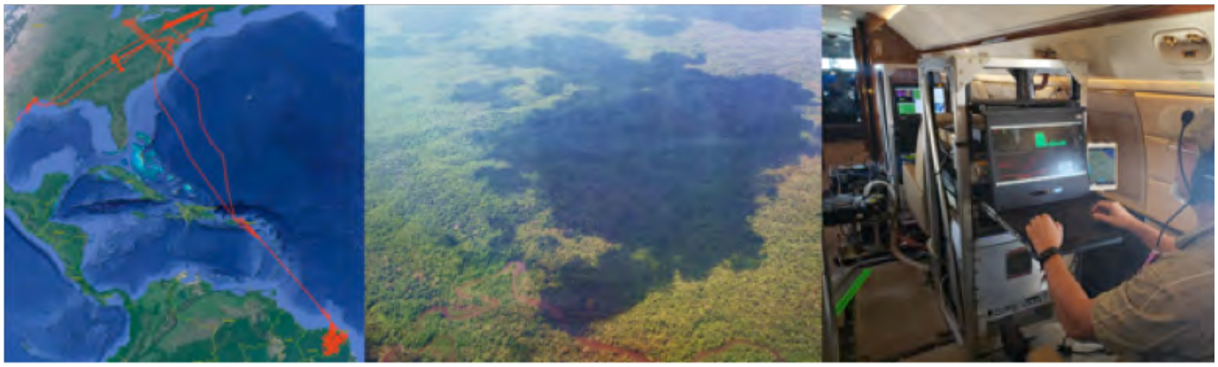


Figure 35. *Left: LVIS/GEDI mission flight tracks flown during the deployment. Center: Oblique view of the dense Guiana Shield forest.* ***Photo Credit:*** *David Rabine Right: LVIS instrument and operator inside the GV.* ***Photo Credit:*** *Rob Switzer*

ASP Support for Instrument Development

FY21 included some flight hours for instrument development, including airborne support for the Earth Science Technology Office (ESTO). Some instruments are being developed specifically for airborne use, while some are being developed as precursors or simulators for satellite instruments. In 2021, ASP aircraft flew the instruments listed in Table 8. Some of these instruments have been developed under sponsorship of ESTO's Instrument Incubator Program (IIP) and Airborne Instrument Technology Transition Program (AITT). ESTO demonstrates and provides technologies that can be reliably and confidently applied to a broad range of science measurements and missions. Through flexible science-driven technology strategies and a competitive selection process, ESTO-funded technologies support numerous Earth and space science missions.

Two projects, the HyperMapping with Hyperspectral Precise Pointing Optical sensor (HYPPOS) and the Compact Midwave Imaging Systems (CMIS), are detailed below.

Table 8. *Instrument development missions supported by airborne activities in FY2021.*

Mission	Flight Hours	Location	Aircraft
Multiband Radiometer (MURI)	31.2	California	Twin Otter
Compact Midwave Imaging System (CMIS)	19.1	From LARC	G-III (L)
UAVSAR imager (QUAKES)	14.9	CA to TX	GV
DAGR	11.8	From WFF	Cessna
HYPPOS	10.2	From WFF	Cessna
Snow Radar (Vanilla UAS)	2.7	WFF	Vanilla-3

HyperMapping with Hyperspectral Precise Pointing Optical Sensor (HYPPOS)

PI – John P. Moison, GSFC/WFF
Program – IRAD
Aircraft – Cessna 206
Payload Instruments – FLIR, Cambot camera, Spectrometers (3)

The HYPPOS project integrated a suite of optical instruments into NASA's Cessna 206 aircraft. These included: a dual axis optical pointing instrument, a FLIR thermal camera, a Cambot high resolution visible camera, two hyperspectral spectrometers, and a Headwall Nanospec push broom spectrometer. Three days of flights were carried out between May 19-20, 2021 and collected over 10 hours of flight data. The primary technical objective was to understand the operational environment of the sensors and to collect test data to develop the dynamic pointing capability for the dual axis pointing instrument. In addition, hyperspectral remote sensing reflectance (Rrs) observations were collected. The Rrs maps will be available as input data for testing and validating several product algorithms for pathfinder activities of the SBG and Surface Topography and Vegetation (SVG) missions. In addition to the airborne observations, several ground-based observations were collected, including observations from Aeronet, Pandora, and Analytical Spectral Devices, Inc. instruments to provide calibration and validation data for the flight observations.

Figure 36. *HYPPOS aircraft instrumentation.*

Compact Midwave Imaging System (CMIS)

PI – Michael Kelly, Johns Hopkins University
Program – ESTO IIP
Aircraft – G-III (Portals)

The first science mission flown on NASA LaRC's G-III was the research flight campaign for the CMIS. CMIS was developed by the Johns Hopkins University's Applied Physics Laboratory (APL) under the sponsorship of ESTO IIP. CMIS successfully completed its flight tests on the G-III on February 9, 2021.

The campaign consisted of four research flights of 16 flight hours preceded by a Compatibility Flight Profile flight with a duration of 3.1 flight hours. The airborne flights evaluated the accuracy/precision and radiometric calibration of CMIS stereo data collected to derive cloud heights, 2D wind fields, and boundary layer aerosol/cloud top height/wind fields at different times of day and night. The science investigations targeted for these observables were coupled cloud-precipitation state and dynamics for monitoring the global hydrological cycle, as well as the impact of Planetary Boundary Layer (PBL) processes on weather, on the transport of pollutants/carbon/aerosols and water vapor, and their interactions with the large-scale circulation. All flights were based out of NASA LaRC. The flights were designed for daytime collection with ground and ocean background, nighttime collection, and daytime collection with snow background and cloud cover. The flights also included flyovers of known targets and an underflight of the Atmospheric Laser Doppler Instrument (ALADIN). The flights covered areas from Lake Erie to Florida.

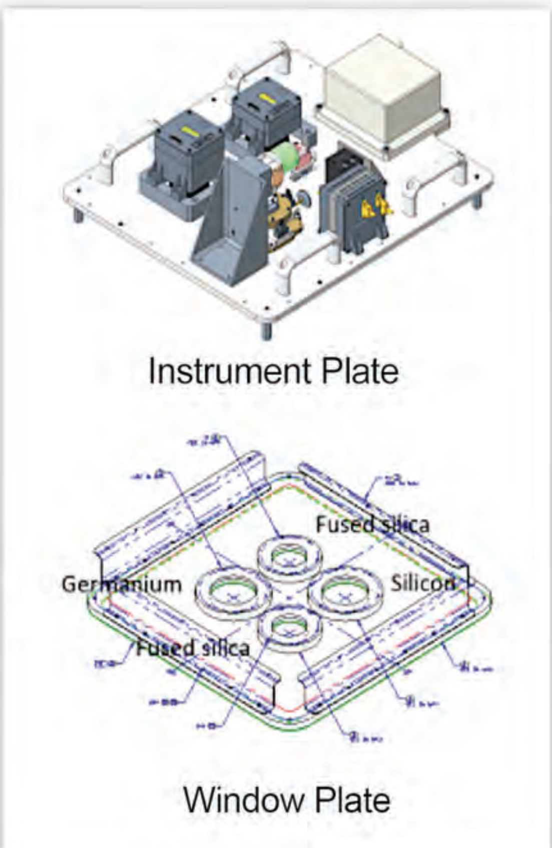


Figure 37. *CMIS installation in LaRC G-III over the aft nadir portal.*

ASP Support to Applied Sciences

In 2021, as in previous years, several flight campaigns supported the NASA Applied Sciences Program or science goals of additional agencies. Of particular interest in 2021 was the opportunity for Airborne Science to work with the Disasters element of Applied Sciences to obtain fire-related imagery during late summer California wildfires. Table 9 lists these and other campaigns with user applications.

Table 9. *Airborne science support to applied science goals.*

Mission	Flight Hours	Location	Aircraft
Fire Response - UAVSAR	16.7	California	G-III (radar)
Oil Spill Disaster	15.6	California	G-III (radar)

Upcoming Activities

Major upcoming missions are listed in Table 10.

Table 10. *Planned major 2022 missions.*

Mission	Aircraft	Location	Science Program
ACCLIP	WB-57, NCAR GV	South Korea	Atmospheric Composition
SABRE (NOAA)	WB-57	From JSC	Atmospheric Composition
CPEX-Cape Verde	DC-8	Cape Verde	Weather and Atmospheric Dynamics
ACTIVATE	HU-25A, UC-12B	North Atlantic	EVS-3
DCOTSS	ER-2	Central US	EVS-3
IMPACTS	ER-2, P-3	U.S. East Coast	EVS-3
S-MODE	G-III, B-200	California (Pacific Ocean)	EVS-3
SHIFT	B-200	Santa Barbara	SBG, PACE
SARP	DC-8	California	SMD R&A
SaSa	P-3	WFF	SMD Science Activation Program
SnowEx	G-III, Twin Otter	Colorado, Alaska	Water and Energy Cycle
ABoVE	G-III, B-200	Alaska	Water and Energy Cycle
WDTS	ER-2	California	Carbon Cycle and Ecosystems
BLUEFLUX	B-200	Florida	Carbon Monitoring System
SMAPVEX	DC-3	Canada	Water and Energy Cycle
SASSIE (Salinity Mission)	DC-3	Canada	Water and Energy Cycle
Ku Snow Radar	Vanilla	Alaska	Climate Variability and Change
AJAX	TBD	California	Atmospheric Composition
LVIS/GEDI	GV	from JSC	Water and Energy Cycle
QUAKES	GV	Western US	Earth Surface and Interior
ICESat-2 Cal/Val	GV	Greenland	Climate Variability and Change

ACCLIP/SABRE

Preparation of the JSC WB-57 for the ACCLIP mission, which includes NOAA as a partner, has provided an opportunity for NOAA to schedule an additional mission on this aircraft using a similar payload suite. The NOAA Stratospheric Aerosol processes, Budget, and Radiative Effects (SABRE) mission, described below, will fly locally from JSC early in 2022, while ACCLIP will take place in July-August 2022, operating from Osan AB, Republic of Korea.

For centuries, the Asian Summer Monsoon (ASM) has been known as a large weather pattern. In recent decades, Earth observing satellites have revealed a large layer at the tropopause level (12 to 18 km altitude) with distinct chemical and aerosol signatures over the monsoon. Figure 38 indicates the location in Korea (★) on the northeast side of this pattern.

Studies suggest this layer is a result of monsoon convection lifting surface air with chemical compounds and particles (aerosols) from populations, industry, agriculture, biological processes, and other activities. The goal of ACCLIP is to measure emissions in this area of convection. Figure 39 shows the location of the field campaign.

Whereas ACCLIP is primarily focused on chemistry, the NOAA SABRE project is primarily focused on aerosol measurements and their contribution to Earth's albedo. The SABRE project is one of a multi-deployment airborne science measurement program to study the transport, chemistry, microphysics, and radiative properties of aerosols in the upper troposphere and lower stratosphere (UTLS) and their impact on the climate system. This campaign will utilize the NASA WB-57 to collect atmospheric data in support of these objectives.

Achieving the SABRE project goals will enable improvements in the representation of stratospheric aerosol-related processes in global models critical to predicting the future climate impact of changes in stratospheric aerosols from natural and anthropogenic sources.

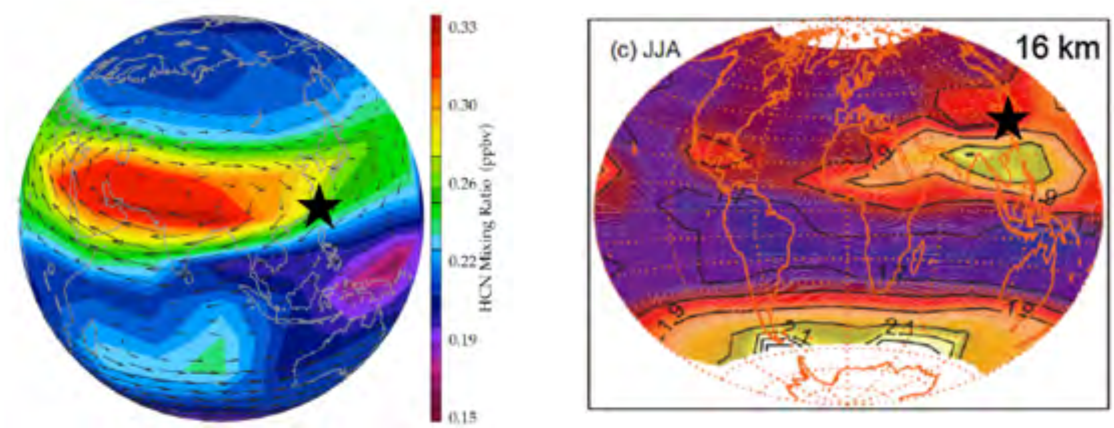


Figure 38. *Asian monsoon models. Left: Hydrogen Cyanide measurements at an altitude of 16.5 km. Right: SAGE II data indicating aerosol extinction at an altitude of 16 km.*

Figure 39. *ACCLIP area of operations for 2022, east between the Republic of Korea and Japan.*

SBG High-Frequency Time Series (SHIFT)

The SBG team has planned an intensive field campaign for Spring 2022. This will involve routine flights of AVIRIS-NG on a commercial B-200 over the Santa Barbara, CA region, including the coast and some distance into the ocean (Figure 40). The March imagery will be compared with May imagery to show seasonal changes between early and late Spring for terrestrial and aquatic vegetation. The coastal focus is on benthic environments and kelp beds/wetlands specifically, which have never been observed sub-seasonally with spectroscopy.

Figure 40. *SHIFT campaign plans.*

EVS-3

EVS-3 missions will continue in 2022. The detailed schedule is shown in Figure 41.

In addition, ASP plans to support instrument development, calibration, and validation activities, and process studies for upcoming missions dedicated to the Designated Observables, Explorer, and Incubation missions described in the 2017 Decadal Survey.[1]

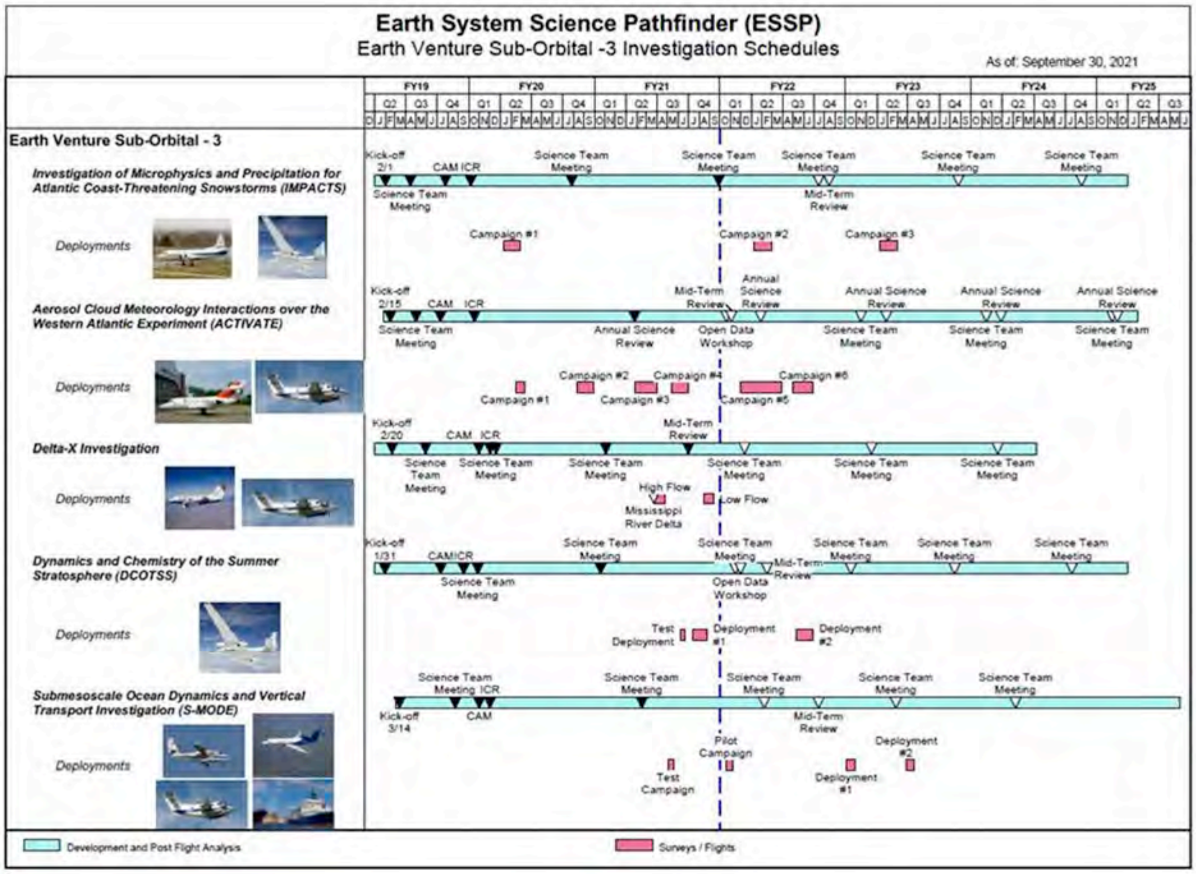


Figure 41. *EVS-3 missions, aircraft, and nominal flight schedules (CY).*

[1]National Academies of Sciences, Engineering, and Medicine. 2018. *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space.* Washington, DC: The National Academies Press. https://doi.org/10.17226/24938.

4. Aircraft

NASA maintains and operates a fleet of highly modified aircraft unique in the world for their ability to support Earth observations. These aircraft are based at NASA Centers. ASP-supported aircraft have direct funding support from ASP for flight hours and personnel. Other NASA aircraft are also available for science missions. In addition, NASA missions employ commercial aviation services (CAS) under protocols established by NASA's Aircraft Office at Headquarters. More information about using these aircraft is provided on the ASP website at: airbornescience.nasa.gov. The annual "call letter," also available on the ASP web site, is an excellent source of information describing how to request airborne services.

FY2021 Highlights

The ASP fleet includes aircraft that can support low and slow flights, as well as those capable of flying high and fast. The aircraft also have a wide variety of payload capacities. Several aircraft modifications and upgrades were completed to ASP platforms in FY21 that either enhance payload capability for the science community or help sustain the aircraft into the future. Highlights are listed in Table 11.

Of particular note are similar modifications to the LaRC G-III and JSC GV that make either aircraft suitable and interchangeable for often-used remote sensing instruments.

Several aircraft are being prepared for sale through GSA in FY22. These are the LaRC Cessna 206H, UC-12B, and HU-25A Guardian/Falcon. The latter two will be sold following ACTIVATE Campaign #6. Future science activities will be transferred to other airborne science platforms, as well as making use of commercial aircraft services.

An infrequent opportunity arose in the summer of 2021 when the ER-2 and WB-57 were flying in geographic proximity for their respective missions, DCOTSS and ACCLIP. As the two aircraft were carrying similar payloads, an intercomparison formation flight was planned and executed at 55,000 ft over the central U.S. The map in Figure 42 shows the locations of the two aircraft during "Test Flight 3." The combination of ACCLIP and NOAA SABRE has moved the WB-57 into the category of partial "ASP-supported" aircraft in FY22.

Table 11. *Enhancement modifications to ASP aircraft in FY21.*

Aircraft	Modification	Impact
Payload Enhancements		
P-3	Nadir port modifications	Payload interchangeability between P-3 nadir ports
	Began permanent installation of ASP data system	Compatibility with ASP-wide data systems
	Pylon aerodynamic modification	Enables use of extended pylons for selected payloads
G-IIIs	Side windows with UV-transparent acrylic	Allows wider frequency band measurements
LaRC G-III / JSC GV	Instrument installations for: CPL, GCAS, HSRL-2, HALO	Enhances science capability
Aircraft Upgrades		
DC-8	Engine repairs & Heavy maintenance check Passenger compartment oxygen system upgraded	Extends platform life Passenger health and safety
ER-2	CARE modifications	Pilot health
GV	Display upgrade Engine overhaul	Enhance science and extend platform life

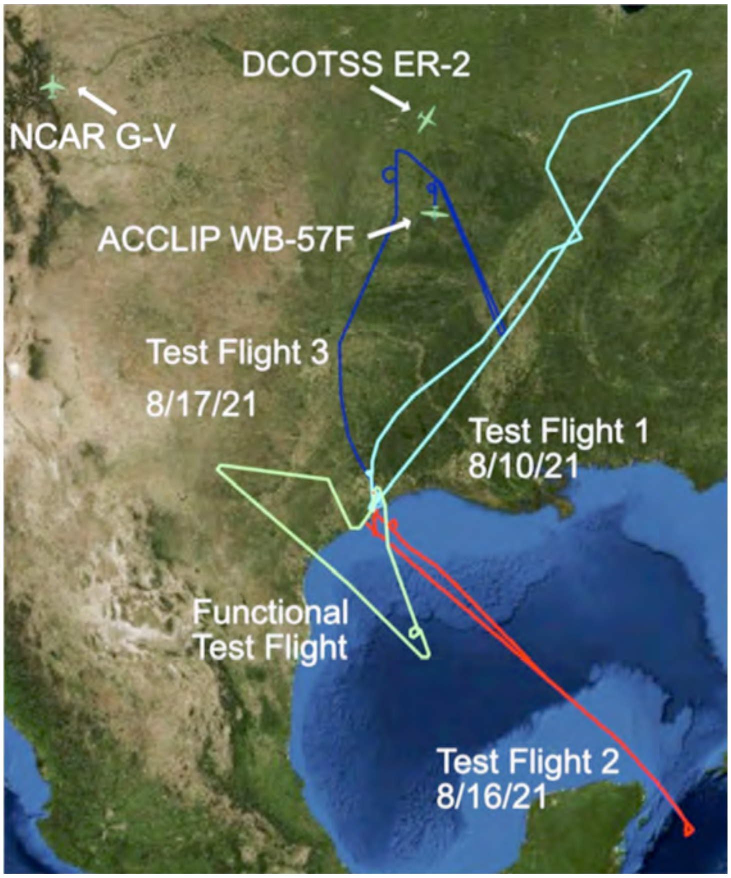


Figure 42. *Map showing locations of the WB-57 and ER-2 for intercomparison flight (Test Flight #3).*

ASP Fleet Summary Characteristics

Aircraft performance characteristics and payload accommodation summaries are listed in Table 12. The fleet of aircraft are shown in Figure 43. The altitude, endurance and range capabilities are shown in Figure 44. Figure 45 indicates payload capability for the aircraft.

Table 12. *Airborne Science Program aircraft and their performance capabilities.*

Platform Name	Center	Payload Accommodations	Duration (Hours)	Useful Payload (lbs)	Max Altitude (ft)	Airspeed (knots)	Range (Nmi)
ASP Supported Aircraft							
DC-8	NASA-AFRC	4 nadir ports, 1 zenith port, 14 additional view ports	12	50,000	41,000	450	5,400
ER-2 (2)	NASA-AFRC	Q-bay (2 nadir ports), nose (1 nadir port), wing pods (4 nadir, 3 zenith ports), centerline pod (1 nadir port)	12	2,900	>70.000	410	5,000
G-III/C-20A	NASA-AFRC	UAVSAR pod	7	2,610	45,000	460	3,000
G-III	NASA-JSC	UAVSAR pod, Sonobuoy launch tube	7	2,610	45,000	460	3,000
G-III	NASA-LaRC	2 nadir ports	7	2,610	45,000	460	3,000
GV	NASA-JSC	2 nadir ports	12	8,000	51,000	500	5,500
P-3	NASA-WFF	1 large and 3 small zenith ports, 3 fuselage nadir ports, 4 P-3 aircraft window ports, 3 DC-8 aircraft window ports, nose radome, aft tailcone, 10 wing mounting points, dropsonde capable	14	14,700	32,000	400	3,800
WB-57 (3)	NASA-JSC	Nose cone, 12 ft of pallets for either 3 ft or 6 ft pallets, 2 Spearpods, 2 Superpods, 14 Wing Hatch Panels	6.5	8,800	>60,000	410	2,500
Other NASA Aircraft							
B-200 (UC-12B)	NASA-LaRC	2 nadir ports, 1 nose port, aft pressure dome with dropsonde tube, cargo door	6.2	4,100	31,000	260	1,250
B-200	NASA-AFRC	2 nadir ports	6	1,850	30,000	272	1,490
B-200	NASA-LaRC	2 nadir ports, wing tip pylons, zenith site for aerosol inlet, lateral ports	6.2	4,100	35,000	275	1,250
C-130	NASA-WFF	3 nadir ports, 1 zenith port, 2 rectangular windows, wing mount for instrument canisters, dropsonde capable, cargo carrying capable	10	36,500	33,000	290	3,200
Cessna 206H	NASA-WFF	Wing pod, belly pod, modified rear window for zenith ports	5.7	1,175	15,700	150	700
Dragon Eye (UAS)	NASA-ARC	*In situ* sampling ports	1	1	>500	34	3
HU-25A Guardian	NASA-LaRC	1 nadir port, wing hard points, crown probes	6	3,000	42,000	430	2,075
Matrice 600 (UAS)	NASA-ARC	Imager gimbal	1	6	8,000	35	3
SIERRA-B (UAS)	NASA-ARC	Interchangeable nose pod for remote sensing and sampling, 1 nadir port	10	100	12,000	60	600
WB-57 (3)	NASA-JSC	Nose cone, 12ft of pallets for either 3ft or 6ft pallets, 2 Spearpods, 2 Superpods, 14 Wing Hatch Panels	6.5	8,800	60,000+	410	2,500

Figure 43. *NASA Earth Science Aircraft Fleet.*

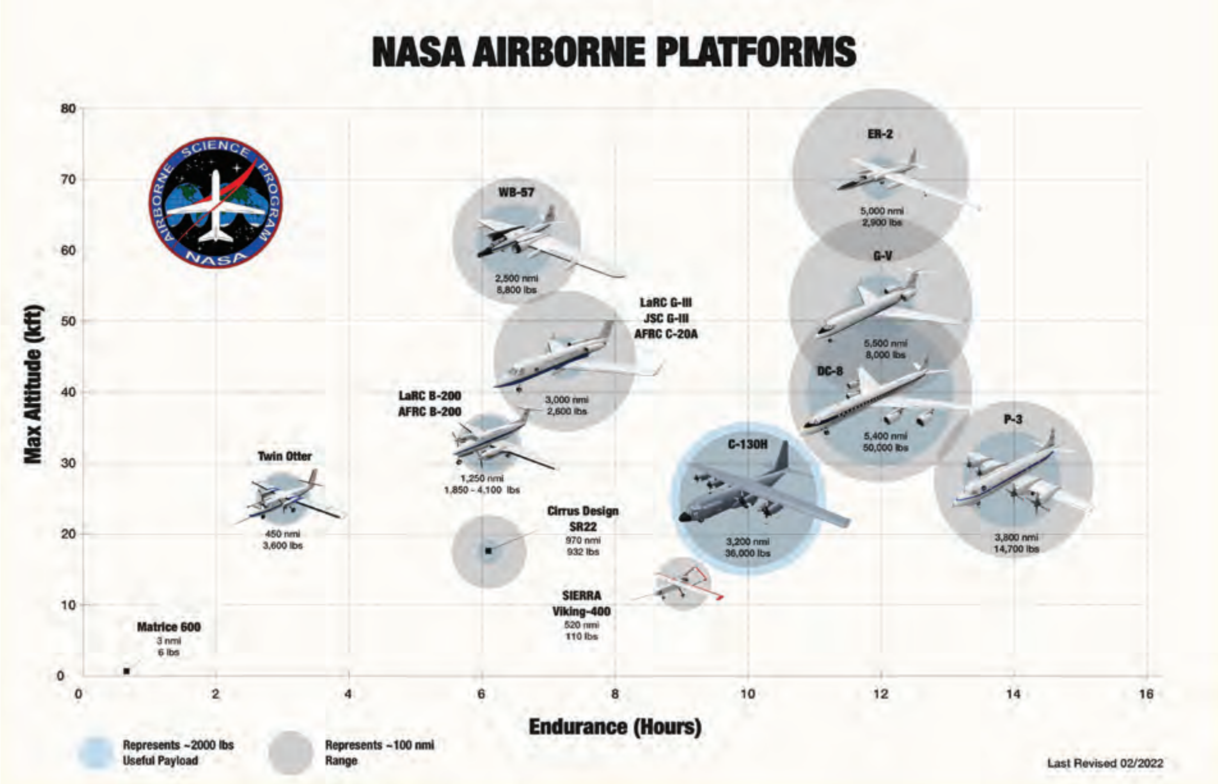


Figure 44. *Aircraft capabilities in Altitude, Endurance, Range and Payload.*

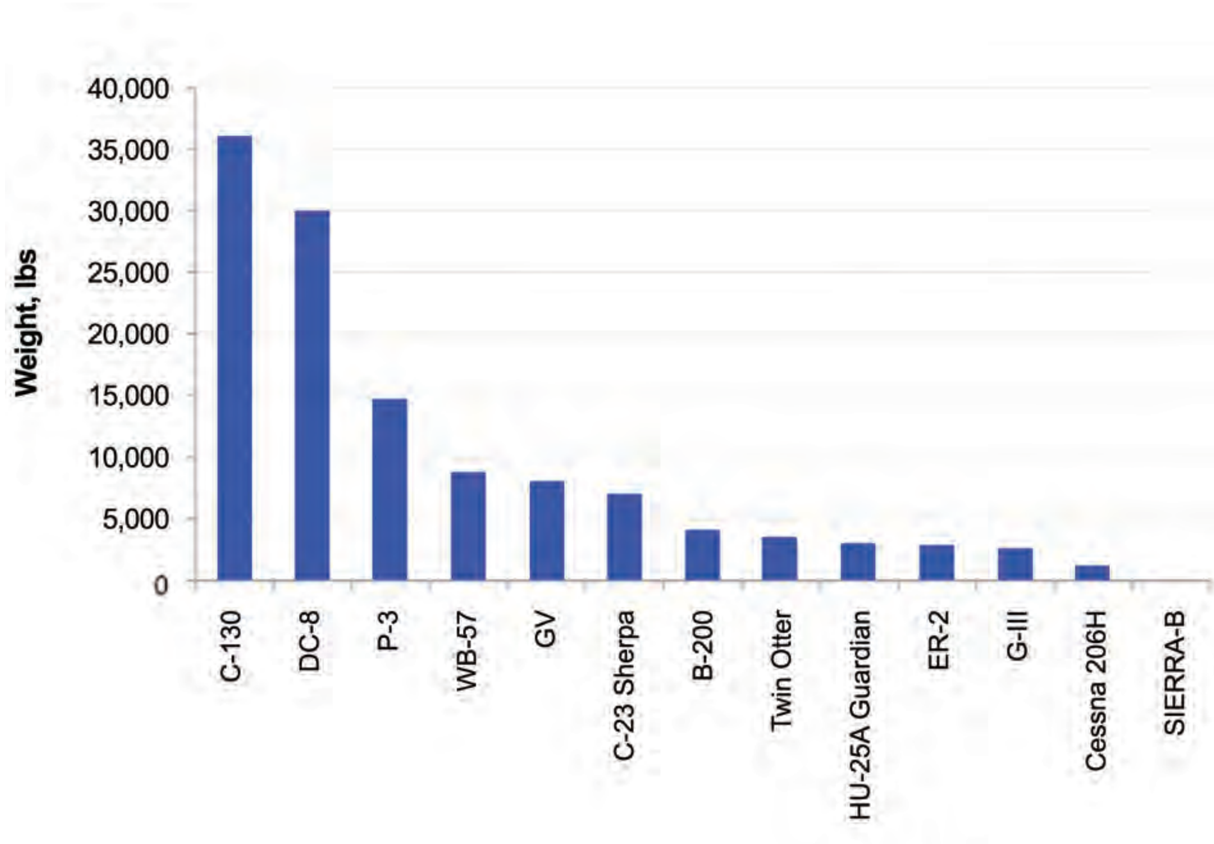


Figure 45. *Useful payload weight of NASA aircraft (SIERRA payload weight is approximately 110 lbs.)*

ASP-Supported Aircraft

The eight aircraft systems ASP directly supported with subsidized flight hours in FY21 were the DC-8 flying laboratory, two ER-2 high altitude aircraft, P-3 Orion, C-20A (G-III), JSC G-III, LaRC G-III, and JSC GV. Beginning in FY22, ASP is also providing flight hour support to a WB-57 at JSC for the ACCLIP and upcoming NOAA/SABRE missions.

DC-8

Operating Center:
Armstrong Flight Research Center (AFRC)

Aircraft Description:
The DC-8 airborne laboratory is a four-engine jet aircraft with a range in excess of 5,000 nm, a ceiling of 41,000 ft, and an experiment payload of 30,000 lbs (13,600 kg). This aircraft, extensively modified as a flying laboratory, is operated for the benefit of airborne science researchers.

FY21 Science Flight Hours: 72.4

DC-8 FY21 Missions

Mission/Project	Location	Science Program Area
CPEX-AW	St. Croix, USVI	Atmospheric Dynamics and Weather

FY21 Modifications and Impacts on Performance/Science:
After FIREX-AQ in FY19, engine inspection identified damage to all four DC-8 engines. Repairs to five engines (including a spare) were processed at an off-site vendor. Two engines were completed in FY20. Repairs to the remainder were completed in early FY21.

Planned upgrades to passenger oxygen system were completed. This upgrade was done because parts were no longer available for overhaul or replacement. The biggest change was to bring all four oxygen bottles into the same loop (the two aft bottles previously were not physically part of the system). This upgraded passenger oxygen system allows the aircraft to have enough oxygen to support the entire cabin for an hour or more in the event the aircraft loses pressure in a situation where the aircraft cannot descend quickly, which can happen during science campaigns when flying near inclement weather.

Significant Upcoming Maintenance Periods:
The DC-8 had major schedule maintenance completed offsite in FY21; the next scheduled major offsite maintenance is in FY26.

Website:
http://airbornescience.nasa.gov/aircraft/DC-8

DC-8 is once again airborne with a takeoff from San Antonio for the ferry flight to Palmdale on May 8

DC-8 maintenance team from VT SAA and AFRC crew prior to ferry fight

Figure 46. DC-8 returns to service following engine refurbishment.

ER-2

Operating Center:
Armstrong Flight Research Center (AFRC)

Aircraft Description:
The ER-2 is a civilian version of the Air Force's U2-S reconnaissance platform. NASA operates two ER-2 aircraft. These high-altitude aircraft are used as platforms for investigations at the edge of space.

FY21 Science Flight Hours: 181.3

ER-2 FY21 Missions

Mission/Project	Location	Science Program Area
WDTS	California	Water and Energy Cycle
DCOTSS	Kansas and surrounding states	EVS-3

FY21 Modifications and Impacts on Performance and Science:
The Cockpit Altitude Reduction Effort (CARE) modification for ER-2 #806 is ongoing and scheduled to be completed in FY22. This modification enhances pilot safety by increasing cockpit pressure, which reduces the effective cockpit altitude from 29,000 ft to 15,000 ft when the aircraft is operating at its cruise altitude of 65,000 feet. Lowering the effective cockpit altitude reduces the chances of decompression sickness known to have short- and long-term effects on the pilot.

Significant Upcoming Maintenance Periods:
ER2 #806 will undergo CARE reassembly and ADS-B Out upgrade with an expected completion of Spring 2022. ER2 #809 will undergo 600-hour maintenance and ADS-B Out upgrade following mission flights with an expected completion by 4QFY23. Both aircraft will continue routine maintenance every 200 and 600 flight hours, respectively. The 200-hour maintenance will take 2-3 weeks to complete each time; the 600-hour maintenance will take 3-4 months.

Website:
http://airbornescience.nasa.gov/aircraft/ER-2

Figure 47. *The ER-2 and DCOTSS team preparing for first test flight.* ***Photo Credit:*** *Caitlin Murphy, ESPO*

P-3 Orion

Operating Center:
Wallops Flight Facility (WFF)

Aircraft Description:
The P-3 is a four-engine turboprop aircraft designed for endurance and range and is capable of long duration flights. The WFF P-3 has been extensively modified to support airborne science-related payloads and activities.

FY21 Science Flight Hours: 0
Due to postponement of IMPACTS EVS-3 mission, the P-3 did not fly science hours in FY21.

P-3 Orion FY21 Missions

Mission	Location	Science Program Area
Maintenance/Pilot Proficiency	WFF	Airborne Science Program

FY21 Modifications and Impacts on Performance and Science:
The P-3 Orion Nadir #3 port mounting holes were standardized and repaired to improve the load carrying capability of this port. A new Nadir #3 standard mounting plate was designed based on port scans to enhance future manufacturing of port plates and window installations to eliminate the need for future matching drilling to the aircraft at this location. Work began in FY21 to support the permanent installation of the ASP data system on the P-3. The new ASP data system will be installed in the Electrical Load Center as well as overhead bin locations thus freeing up additional rack and seat locations on the cabin floor for additional science installations. The new ASP data system is scheduled for installation in May 2022.

Pylon extension work was also completed in 2021, in advance of the upcoming IMPACTS flights.

Significant Upcoming Maintenance Periods:
- Phased Depot Maintenance (PDM) – March 2023, 10 months (The WFF Aircraft Office is investigating a Conditions Based Maintenance (CBM) program for future use beyond PDM.)
- Landing Gear Overhaul – March 2025, 1-2 months (This date may change because of CBM.)
- Annual Maintenance – 2021-2026, 4-6 weeks each year (This maintenance can be scheduled to support mission needs; durations may change due to CBM.)

Website:
http://airbornescience.nasa.gov/aircraft/P-3_Orion

Figure 48. *The P-3 aircraft at WFF. (File photo)*

Remote Sensing GV

Operating Center:

Johnson Space Center (JSC)

Aircraft Description:

The Gulfstream V (GV) is a long-range, large business jet aircraft built by Gulfstream Aerospace, derived from the Gulfstream IV. It flies up to Mach 0.885, at up to 51,000 feet, and has a range of 5,000 nautical miles. JSC procured the GV in 2016 as part of a shared usage agreement between the ISS Program and NASA ESD. The ISS program uses the GV for Crew Return missions and ESD uses it to support airborne science missions in remote locations around the world.

FY21 Science Flight Hours: 167.4

GV FY21 Missions

Mission	Location	Science Program Area
LVIS/GEDI	Baltimore, MD, Puerto Rico, French Guiana	Water and Energy Cycle
Tracer-AQ	Houston, TX	Atmospheric Composition
QUAKES	Southern California	Earth Surface and Interior

FY21 Modifications and Impacts on Performance and Science:

Display upgrade and engine overhaul were performed. Display upgrade does not immediately impact science, but it ensures the avionics are supportable for the foreseeable future, allowing the GV to maintain coverage under the avionics maintenance plans, which help control costs and minimize downtime.

Instrument installations for the CPL, GCAS, HSRL-2, and HALO were completed.

Significant Upcoming Maintenance Periods:

None.

Website:

https://airbornescience.nasa.gov/aircraft/GV_-_JSC

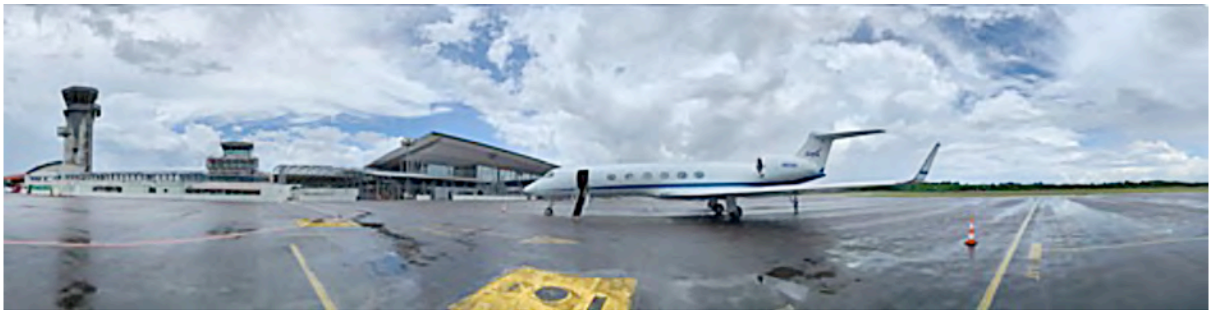


Figure 49. *The GV on the tarmac during a brief stopover in Cayenne, French Guiana during the LVIS/GEDI mission.*
Photo Credit: *Bryan Blair*

Gulfstream III (G-III)

NASA ASP supports three G-III aircraft for Earth Science: one at AFRC, one at JSC, and as of 2020, one at LaRC. The G-III is a business jet with routine flight at 40,000 feet.

The AFRC and JSC platforms have been structurally modified and instrumented to carry the payload pod for the three versions of JPL's UAVSAR instrument (L-band, P-band, Ka-band). The LaRC G-III does not carry the pod, but has been modified with nadir portals to support remote sensing payloads. Features specific to each aircraft, along with science activities undertaken in FY21, are described below.

UAVSAR G-III (AFRC)

Operating Center:
Armstrong Flight Research Center (AFRC)

FY21 Science Flight Hours: 261.3

C-20A (G-III) FY21 Missions

Mission	Location	Science Program Area
Delta-X	New Orleans, Louisiana	EVS-3
L-band Engineering	Southern California	Earth Surface and Interior
P-band Engineering	Southern California	Water and Energy Cycle
P-band Pacific Northwest	Seattle, WA, Portland, OR,Northern California	Water and Energy Cycle
ASAR	California, Alaska, Great Lakes, Louisiana, Maine, Oregon, Washington	Climate Variability and Change
California Fault Lines	California	Earth Surface and Interior
Landslides	California	Earth Surface and Interior
Hayward Fault	California	Earth Surface and Interior
Emergency Response	New Orleans, LA – Hurricane Southern California – Fire	Applied Science

FY21 Modifications and Impacts on Performance and Science:
None.

Website:

http://airbornescience.nasa.gov/aircraft/G-III_C-20A_-_Armstrong

Significant Upcoming Maintenance Periods:

- Engine overhaul: 2 months in FY22-23
- 72-month inspection: 2 months in FY22-23

The C-20A maintenance schedule is updated on the ASP website.

Figure 50. *The AFRC C-20A flew SAR imagery missions for ASAR, Delta-X, and Earth Surface missions.*

UAVSAR G-III (JSC)

Operating Center:

Johnson Space Center (JSC)

The JSC G-III carried L-band and P-band versions of the SAR in 2020.

FY21 Science Flight Hours: 247.8

JSC G-III FY21 Missions

Mission	Location	Science Program Area
SnowEx	Western CONUS	Water and Energy Cycle
Delta-X	Mississippi River Delta	EVS-3
Eel River Landslides	California	Earth Surface and Interior
Santa Barbara Oil Slick	Santa Barbara, CA	Applied Science
SHARC/Hayabusa2	Australia	Planetary Science
Engineering/Calibration	California	Climate Variability and Change

FY21 Modifications and Impacts on Performance and Science:

Side optical windows were used operationally on the GIII for the first time in FY21. An AFRC design was adapted for the mission but used a special UV-transparent acrylic to allow for wider-band measurements. In total, four additional side optical windows were fabricated, bringing the total to six for all of ASP's G-III aircraft.

Significant Upcoming Maintenance Periods:

- 72-month maintenance starting in Dec 2022, ~3-4 months
- Engine Swap in early CY2023, ~2 months
- Engine Swap in early CY2024, ~2 months

Website:

https://airbornescience.nasa.gov/aircraft/G-III_-_JSC

Figure 51. *The JSC G-III flew SAR imagery flights for SnowEx and Delta-X, among others.*

Remote Sensing G-III

Operating Center:
Langley Research Center (LaRC)

Aircraft Description:
The Gulfstream III (a former U.S. Air Force C-20B) aircraft became available for NASA science during FY20. The nadir portals (each 18.16 in. x 18.16 in. with external shutters) allow the aircraft to support Earth science sensors. The G-III can be equipped with pressure domes over the portals so instruments can be flown open to the atmosphere. Six Researcher Interface Panels are being installed in the passenger cabin, which will accommodate up to ten researchers. The research system will also accommodate the NASA Airborne Science Data and Telemetry (NASDAT) system. The G-III aircraft has an advertised range of 3750 nm.

FY21 Science Flight Hours: 247.8

Mission	Location	Science Program Area
SHARC (Hayabusa)	Australia	Planetary Sciences
MOOSE	Detroit, MI	Atmospheric Composition
CMIS	NASA LaRC	ESTO-IIP
KiNET-X	Iceland	Heliophysics

FY21 Modifications and Impacts on Performance and Science:
Aircraft is in flight status with no platform modifications since last year. Instrument installations for the CPL, GCAS, HSRL-2, and HALO were completed.

Significant Upcoming Maintenance Periods:
Semi-annual maintenance, 72-month inspection, FY22.

Website:
https://airbornescience.nasa.gov/aircraft/G-III_-_JSC

Figure 52. *The NASA LaRC G-III (N520NA) configured for CMIS mission.*

WB-57 High Altitude Aircraft

Operating Center:
Johnson Space Center (JSC)

Aircraft Description:
The WB-57 is a mid-wing, long-range aircraft capable of operation for extended periods of time from sea level to altitudes in excess of 60,000 feet. The sensor equipment operator (SEO) station contains navigational equipment and controls for operation of the payloads located throughout the aircraft. The WB-57 can carry up to 8800 lbs of payload. JSC maintains three WB-57 aircraft.

FY21 Science Flight Hours: 18.9

WB-57 FY21 Missions

Mission/Project	Location	Science Program Area
ACCLIP Test Flights	Texas	Atmospheric Composition

FY21 Modifications and Impacts on Performance and Science:
None; the aircraft team will support the ACCLIP and SABRE science missions in FY22.

Website:
http://airbornescience.nasa.gov/aircraft/WB-57

Figure 53. *The WB-57 will fly ACCLIP mission flights in FY22.*

Other NASA Earth Science Aircraft

Other NASA aircraft, as described here, on the Airborne Science website, and in the annual ASP Call Letter, are platforms operated by NASA centers. Although not subsidized by the ASP program, these aircraft are also modified to support Earth-observing payloads. These aircraft are available for science through direct coordination with the operating center.

Table 13. *Other NASA aircraft available for Earth Science missions.*

Aircraft	Operating Center
B-200 King Air; UC-12B	LaRC, AFRC, or contracted
HU-25A Falcon/HU-25C Guardian	LaRC
Cessna 206H	LaRC
G-IV	LaRC
SIERRA-B	ARC
Small UAS	AFRC, ARC, LaRC, JPL
SR22	LaRC
Twin Otter	GRC or contracted

B-200 / UC-12

Operating Center:

Langley Research Center (LaRC), Armstrong Flight Research Center (AFRC)

Aircraft Description:

The Beechcraft B-200 King Air is a twin-turboprop aircraft capable of mid-altitude flight (>30,000 ft) with up to 1000 lbs of payload for up to 6 hours. LaRC operates a conventional B-200 and a UC-12B (military version). AFRC operates a Super King Air B-200 that has been modified for downward-looking payloads. This aircraft was flown to ARC in September 2021 for S-MODE flights and completed the entire mission off the coast of San Francisco before returning to AFRC.

The three B-200 aircraft have varying modifications to support science, as listed in Table 12.

B-200 FY21 Missions

Aircraft	Mission	Location	Science Program Area	FY21 Flight Hours
UC-12B	ACTIVATE	LaRC; Atlantic Ocean	EVS-3	180
B-200 (LaRC)	SLAP/LIASE	Spain	Water and Energy Cycle	98
B-200 (AFRC)	S-MODE	California	EVS-3	25

FY21 Modifications and Impacts on Performance and Science:

None.

Significant Upcoming Maintenance Periods:

The maintenance schedule for AFRC B-200 (NASA801) depends on hours flown.

UC-12B to be sold via GSA following ACTIVATE Campaign #6.

Websites:

http://airbornescience.nasa.gov/aircraft/B200_-_LARC

http://airbornescience.nasa.gov/aircraft/B-200_UC-12B_-_LARC

http://airbornescience.nasa.gov/aircraft/B200_-_AFRC

Figure 54. *LaRC B-200 aircraft. (File photo)*

Figure 55. *AFRC B-200 arrives at ARC for S-MODE.*

HU-25A Falcon/Guardian

Operating Center:
Langley Research Center (LaRC)

Aircraft Description:
The HU-25C and HU-25A Falcons are modified twin-engine business jets based on the civilian Dassault FA-20G Falcon. The HU-25A is currently in active service.

FY21 Science Flight Hours: 173.4

HU-25A FY21 Missions

Mission	Location	Science Program Area
ACTIVATE	NASA LaRC – Atlantic Ocean	EVS-3
CMIS Support	NASA LaRC	ESTO-IIP

FY21 Modifications and Impacts on Performance and Science:

None.

Significant Upcoming Maintenance Periods:
Airplane to be sold via GSA following ACTIVATE Campaign #6.

Website:

http://airbornescience.nasa.gov/aircraft/HU-25C_Guardian

Figure 56. *The HU-25A and UC-12B outside of the NASA LaRC aircraft hangar during ACTIVATE.*
Photo Credit: *David C. Bowman*

CESSNA 206H

Operating Center:

Langley Research Center (LaRC)

Aircraft Description:

The NASA LaRC Cessna 206H is an all-metal, six-seat, high-wing, single-engine general aviation airplane equipped with tricycle landing gear and is designed for general utility purposes. The aircraft was acquired by NASA in 2001 to provide a low-cost research platform for advanced pilot displays and to serve as a platform for atmospheric science instruments. The aircraft has been reconfigured for science. In addition to internal space in the aft section of the cabin for instrumentation, up to 300 lbs can be carried in the Cessna production belly cargo pod and 100 lbs in a custom-designed pod that attaches to the right-wing strut. The aircraft is equipped with NASA LaRC's General Aviation Baseline Research System, which includes GPS, the Air Data, Attitudes, and Heading Reference System (ADAHRS), out-the-window video, a Researcher Workstation, and control position transducers on the aileron, rudder, elevator, pitch trim, and throttle.

FY21 Science Flight Hours: 26.1

CESSNA 206H FY21 Missions

Mission	Location	Science Program Area
EPA TEROS	NASA LaRC – Atlantic Ocean	EPA
DAGR	NASA LaRC	Atmospheric Composition
HYPPOS	NASA LaRC	Carbon Cycle and Ecosystems

FY21 Modifications and Impacts on Performance and Science:

None.

Cessna 206H (N504NA) is being prepared for GSA sale in FY22.

Website:

http://airbornescience.nasa.gov/aircraft/Cessna_206H

SIERRA-B UAS

Operating Center:
Ames Research Center (ARC)

Aircraft Description:
The Sensor Integrated Environmental Remote Research Aircraft (SIERRA)-B aircraft is a high wing, 480-lb gross weight monoplane (UAS Class III) with twin tail booms and inverted V-tail. It can perform remote sensing and atmospheric sampling missions in isolated and often inaccessible regions, such as over mountain ranges, the open ocean, or the Arctic/Antarctic. UAS missions are of particular value when long flight durations or range-measurement requirements preclude a human pilot or where remote or harsh conditions place pilots and high-value aircraft at risk. Designed by the U.S. Naval Research Laboratory and developed at NASA ARC, the SIERRA-B is well suited for precise and accurate data collection missions because it is large enough to carry up to 100 lbs of scientific instruments and fly up to 12,000 feet, yet is small enough not to require a large runway or hangar. The SIERRA-B Program, managed at ARC, is focused on providing end-to-end support for UAS flight missions in support of Earth science research and applications activities. The program has capabilities to support all phases of UAS missions, including experiment design, requirements definition, payload integration design and support, airworthiness and flight safety reviews, airspace access including COA development, deployment planning, mission planning, and flight operations.

FY21 Science Flight Hours: 0

FY21 Modifications and Impacts on Performance and Science:
None.

Significant Upcoming Maintenance Periods:
Maintenance is a function of number of flight hours flown.

Website:
http://airbornescience.nasa.gov/aircraft/SIERRA_-_ARC

Figure 57. *The SIERRA UAS.*

Progress on using Uncrewed Aircraft Systems (UAS) for Earth Science

UAS capabilities continue to expand and scientific interest continues to grow, as evidenced by the number of sessions at workshops that focus specifically on their use across a variety of disciplines. The latest National Academies report, entitled Airborne Platforms to Advance NASA Earth System Science Priorities: Assessing the Future Need for a Large Aircraft (2021)[2], frequently referenced the important role UAS aircraft can play in enabling measurements that are difficult or impossible with crewed aircraft. The regulatory environment continues to limit more routine operations of UAS, given limited progress in enabling flights beyond visual line of site (BVLOS) of the pilot, and federal agencies have been prohibited from using and purchasing the most capable and cost-effective multi-rotor UAS produced by the Chinese DJI Corporation. Some of the ways ASP continues to support use of UAS for Earth science are highlighted below.

This year the NASA SMD funded a project led out of the GSFC Cryospheric Sciences Laboratory to integrate and test the University of Kansas miniaturized snow radar on the Vanilla UAS (Platform Aerospace LLC). This Medium Altitude Long Endurance (MALE) UAS is a fixed-wing diesel powered aircraft capable of carrying 30-50 lbs of payload for over a week. The aircraft was designed and prototyped under a NASA SBIR project that was supported by ARC and WFF. The GSFC-led project conducted flight testing of the UAS with new payload wing pods at AFRC in February 2021 as well as a FCF out of WFF in August 2021 in preparation

Figure 58. *The Vanilla UAS in Alaska.* ***Photo Credit:*** *Brooke Medley, GSFC*

[2]National Academies of Sciences, Engineering, and Medicine. 2021. ***Airborne Platforms to Advance NASA Earth System Science Priorities: Assessing the Future Need for a Large Aircraft.*** Washington, DC: The National Academies Press. https://doi.org/10.17226/26079.

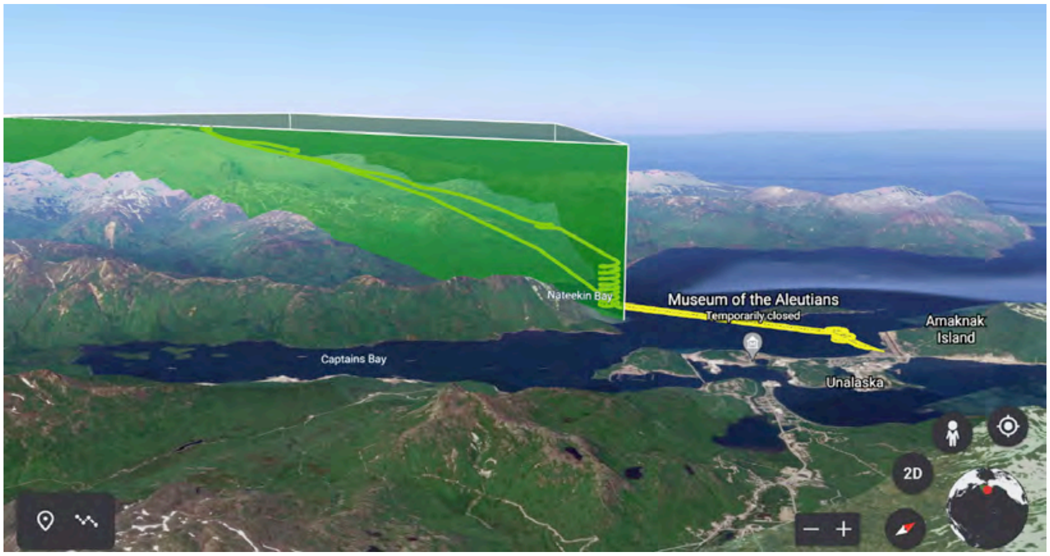


Figure 59. *A 3D map showing the flight track of the S2 UAS during a joint USGS/NASA science flight over Makushin Volcano, with the Temporary Flight Restriction indicated in green.*

for field testing at Deadhorse, AK in October 2021. The ARC Airborne Science Office consulted on SATCOM solutions as well as risk reduction for icing conditions based on experience with the SIERRA-B UAS.

Platform Aerospace also performed cold-room testing on the Vanilla UAS, installed icing sensors, and painted leading edges in an ice-shedding paint in preparation for the extreme polar conditions expected up north. The Alaska deployment was the first test of the UAS in extreme cold conditions with ground temperatures hovering near 0°F. After ice accumulation was discovered on the UAS propeller during ground testing at the airport, a new propeller with ice-shedding paint was sent to Alaska. The project completed a 6+ hour flight out of Deadhorse, AK in early November 2021 surveying snow depths over Arctic sea ice following an ICESat-2 ground track, proving the mission concept.

In September 2021, the Black Swift S2 UAS was used by the U.S. Geological Survey (USGS) to conduct BVLOS flights over the Makushin Volcano in Alaska to collect gas samples of the plume and to conduct infrared measurements of the active crater. ARC provided airworthiness oversight and assisted with obtaining a Certificate of Authorization (COA), as well as a BVLOS waiver from the FAA. The Anchorage FAA Center set up a warning area around the volcano and this facilitated safe and effective operations that launched from the airport at Dutch Harbor. The S2 was originally funded through a NASA SBIR award inspired by the success of the Dragon Eye UAS that was operated by ARC in support of volcanic plume sampling missions in 2013 and 2017.

The Airborne Science Program also continues to explore the potential for High Altitude Long Endurance (HALE) UAS to provide high spatial and temporal resolution measurements for a variety of science disciplines. Following a successful SBIR Phase II flight test of the Swift Ultra Long Endurance (SULE) UAS in FY20, ARC partnered with the U.S. Forest Service (USFS) to support a fire imaging demonstration. That flight is now scheduled for July 2022. ARC will be providing airworthiness reviews as well as assisting with the COA and BVLOS waiver for operations out of SpacePort America. The project has also received a Phase II extension with additional funding to enable a NASA science demonstration following the USFS flight.

Figure 60. *S2 UAS on the launcher at Dutch Harbor airport following inspection by Matt Burgess (USGS).*
Photo Credit: *Jack Elston (Black Swift LLC) and Christoph Kern*

5. Aircraft Cross-Cutting Support and IT Infrastructure

Aircraft support entails aircraft facility instrument operations and management, engineering support for payload integration, flight planning and mission management tools, flight navigation data hardware and software support, and flight data archiving and distribution.

Cross-cutting support for ASP missions is managed at ARC and supported by the Universities Space Research Association (USRA) Airborne Sensor Facility (ASF) and Bay Area Environmental Research Institute (BAERI) National Suborbital Research Center (NSRC). Specific activities include providing facility instruments, satellite communications, mission tools data services, and assistance with payload integration engineering.

Further support for mission management and real-time flight tracking is provided by ARC through the Mission Tools Suite (MTS).

ASP Facility Science Infrastructure

Facility Instrumentation

The ASP provides a suite of facility instrumentation and data communications systems for community use by approved NASA investigators. Currently available ASP instrumentation (Table 10) includes standalone precision navigation systems, a suite of digital tracking cameras and video systems, and various air data measurement instruments. Real-time data communications capabilities, which differ from platform to platform, are also described below, and are integral to a wider Sensor Network architecture. In addition, ESD, through the Research and Analysis (R&A) Program and EOS Project Science Office, maintains a suite of advanced imaging systems that are made available to support multidisciplinary research applications. These are supported at various NASA field centers, including JPL, ARC, and LaRC. The ASF also maintains a spectral and radiometric instrument calibration facility, which supports the wider NASA airborne remote sensing community. Access to any of these assets is initiated through the ASP Flight Request process (see page 9).

Sensor Network IT Infrastructure

A state-of-the-art real-time data communications network has been implemented across the ASP core platforms. Utilizing onboard Ethernet networks linked through airborne satellite communications systems to the web-based

MTS, the sensor network is intended to maximize the science return from single-platform missions and complex multi-aircraft science campaigns. It leverages data visualization tools developed for the NASA DC-8, remote instrument control protocols developed for the Global Hawk aircraft, and standard data formats devised by the Interagency Working Group for Airborne Data and Telecommunication Systems (IWGADTS). The sensor network architecture includes standardized electrical interfaces for payload instruments, using a common Experimenter Interface Panel (EIP); an airborne network server and satellite communications gateway known as the NASA Airborne Science Data and Telemetry (NASDAT) system; and a web-based application programming interface (API) for interfacing to customer software and other agencies. These capabilities are now operational, as indicated in Table 14.

Table 14. *Facility equipment.*

Airborne Science Program Facility Equipment		
Instrument / Description	Supported Platforms	Support Group
Digital Mapping System (DMS), 21 MP Natural Color Cameras	Most ASP Platforms	ASF/ARC
POS AV 510 (3) Applanix Position and Orientation Systems, DGPS w/Precision IMU	All ASP Platforms	3 at ASF/ARC
POS AV 610 (2) Applanix Position and Orientation Systems, DGPS w/Precision IMU	All ASP Platforms	2 at ASF/ARC 2 at WFF
Dew Point Hygrometers	DC-8, P-3	NSRC
IR Surface Temperature Pyrometers	DC-8, P-3	NSRC
LN-251 Embedded GPS/INS Position and Orientation System	DC-8, P-3	NSRC
Combined Altitude Radar Altimeter	DC-8	NSRC
Forward and Nadir 4K Video Systems	DC-8, P-3	NSRC
Total Air Temperature Probes	DC-8, P-3	NSRC
Ice Detector	DC-8	NSRC
MVIS 4K Video Camera (nadir)	ER-2	ASF/NSRC
Pan-Tilt-Zoom (PTZ) Camera	ER-2	ASF/NSRC
FLIR Vue Pro R 640 IR Camera (45° and nadir)	DC-8	NSRC
45° HD Video Camera	DC-8	NSRC
EOS and R&A Program Facility Instruments		
Instrument / Description	Supported Platforms	Support Group
MODIS/ASTER Airborne Simulator (MASTER) 50 ch Multispectral Line Scanner V/SWIR-MW/LWIR	B200, DC-8, ER-2, P-3, WB-57	ASF/ARC
Enhanced MODIS Airborne Simulator (MAS) 38 ch Multispectral Scanner	ER-2	ASF/ARC
Pushbroom Imager for Cloud and Aerosol R&D (PICARD) 400 – 2450 nm range, $\Delta\lambda$ 10 nm	ER-2	ASF/ARC
AVIRIS-ng Imaging Spectrometer (380 – 2510 nm range, $\Delta\lambda$ 5 nm)	Twin Otter, B200	JPL
Portable Remote Imaging SpectroMeter (PRISM) (350 – 1050 nm range, $\Delta\lambda$ 3.5 nm)	Twin Otter, ER-2, GV, LaRC G-III	JPL
AVIRIS Classic Imaging Spectrometer (400 – 2500 nm range, $\Delta\lambda$ 10 nm)	ER-2, Twin Otter	JPL
UAVSAR Polarimetric L-band Synthetic Aperture Radar, Capable of Differential Interferometry	G-III/C-20	JPL
NAST-I Infrared Imaging Interferometer (3.5 – 16 mm range)	ER-2, DC-8	LaRC

NASA Airborne Science Data and Telemetry (NASDAT) System

The NASDAT provides experiments with: :

- Platform navigation and air data
- Highly accurate time-stamping
- Baseline Satcom, Ethernet network, and Sensor-Web communications
- Legacy navigation interfaces (RS-232, RS-422, ARINC-429, Synchro, IRIG-B)
- Recorded cockpit switch states on the ER-2 and WB-57 aircraft
- Optional mass storage for payload data

In FY21, development efforts continued on the next generation of onboard information technology in support of science payloads. One of the goals of this effort is to investigate more modular, upgradeable systems that will enable incremental improvements as sub-system element improvements become available.

Satellite Communications Systems

Several types of airborne satellite communications systems are currently operational on the core science platforms. A high bandwidth Ku-band system, which uses a large steerable dish antenna, is installed on the WB-57. Inmarsat Broadband Global Area Network (BGAN) multi-channel systems, using electronically-steered flat panel antennas, are available on many of the ASP core and other NASA aircraft. Data-enabled Iridium satellite phone modems are also in use on most of the science platforms. Although Iridium has a relatively low data rate, unlike the larger systems it operates at high polar latitudes and is lightweight and inexpensive to operate. Satcom capabilities are listed in Table 15.

Payload Management

ASP provides a variety of engineering support services to instrument teams across all program platforms. These include mechanical engineering, electrical and network interface support, and general consulting on operational issues associated with specific aircraft. The services are provided jointly by personnel from NSRC and ASF.

NSRC staff provides science instrument integration services for the NASA DC-8 aircraft. Instrument investigators provide a Payload Information Form (PIF) that includes basic instrument requirements for space, power, aircraft data, location of the instruments, and any applicable inlet or window access needs. The staff then uses this, along with additional solicited information, to complete engineering design and analysis of new instrument and probe installations on the aircraft, along with wiring, data, and display feeds to instrument operators. As availability

Table 15. *Satellite communications systems on ASP aircraft.*

Satcom System Type/Data Rate/Nominal	Supported Platforms	Support Group
Ku-Band (1 channel system) / > 1 Mb/sec	WB-57	NSRC; AFRC; JSC
Inmarsat BGAN (2 channel systems) / 432 Kb/sec per channel	DC-8, WB-57, P-3, AFRC B200, ER-2, GV, HU-25A	NSRC, ASF, JSC
Iridium (1-8 channel systems) / 9.6 Kb/sec per channel (each NASDAT contains a 4-channel system))	Most ASP Platforms	NSRC: ASF

permits, crosscutting instrument integration support has also been supplied intermittently on additional ASP aircraft.

NSRC also provides full-featured data display, aircraft video, facility instrument, and satcom services on the DC-8 and P-3. A high-speed data network (wired and wireless) is maintained on each of the aircraft to provide on-board investigators access to display data available on the aircraft. Video, aircraft state parameters, and permanent facility instrument data are recorded, quality-controlled, and posted to the science mission and ASP data archives. Satcom services are provided with multichannel Iridium and high bandwidth Inmarsat services. These services allow for real time chat with scientists on the ground and other aircraft. NSRC engineers also work with investigators to send appropriate data up to and down from the aircraft to allow for real time situational awareness to scientists on the ground and in flight. Subsets of these systems are provided on several other ASP aircraft, including the ER-2, G-III/C-20s, GV, UC-12B, and HU-25A.

Along with general payload engineering services, the Ames Crosscutting team designs and builds custom flight hardware for the ASP real-time sensor network (i.e., network host and navigation data server (NASDAT)) and standardized EIPs. ASF personnel also support the ER-2 program, providing payload integration and field operations support, as required for the real-time sensor network and multiple video systems.

Mission Tool Suite

The NASA Airborne Science Mission Tool Suite (MTS) supports ASP and ESD by providing a suite of graphical capabilities to support airborne science missions. The primary goal of MTS is to provide a common operating picture for improved situational awareness for all participants in airborne missions from scientists and engineers to managers, as well as the general public (who have access to the asset tracking map). The intent of the system is to encourage more responsive and collaborative measurements between instruments on multiple aircraft, satellites, and on the surface to increase the scientific value of the measurements and improve the efficiency and effectiveness of flight missions.
Following release of the updated MTSv2 in 2020 (https://mts2.nasa.gov), the development team has focused on refinement of the MTS application interface. These changes have been folded into the v2.5.0 release, available in December 2021. Version 2.5.0 includes a handful of customer-requested updates. One such request is a more capable Distance Tool. The revamped distance tool adds time estimation, new multipoint editing features such as multipoint selection, point transformations, undo, point labels, custom icons, among other improvements. The MTS team will continue to enhance this tool over the coming months. The v2.5.0 release also brings numerous improvements for more rapidly accessing recent meteorological information (e.g., METAR/TAF), predicted satellite trajectories, and searchable mission products, including navigational and administrative geospatial lookups. All information is now accessible directly from the Search interface within the MTS Mission Monitor. The MTS data service API software is responsible for aggregating and serving airspace, meteorological, navigational and other real-time data from the FAA. It is equipped with web services for working with hierarchical data, geospatial conversion, and data serialization. Contact the MTS team to utilize these services.
The MTS team is very appreciative to have worked with so many great teams across NASA and NOAA to advance new operational capabil-

ities to the airborne science community. The new Nystrom Line tool automatically locates nearby navigational aids and provides a magnetic corrected summary to simplify plan coordination. A new capability provides a web standards interface for frequently-used Geostationary Lightning Mapper (GLM) products derived from GOES Gridded data. This capability was put into immediate use for the ACCLIP, DCOTTS, and HALE-X missions, and will greatly enhance future mission operations.

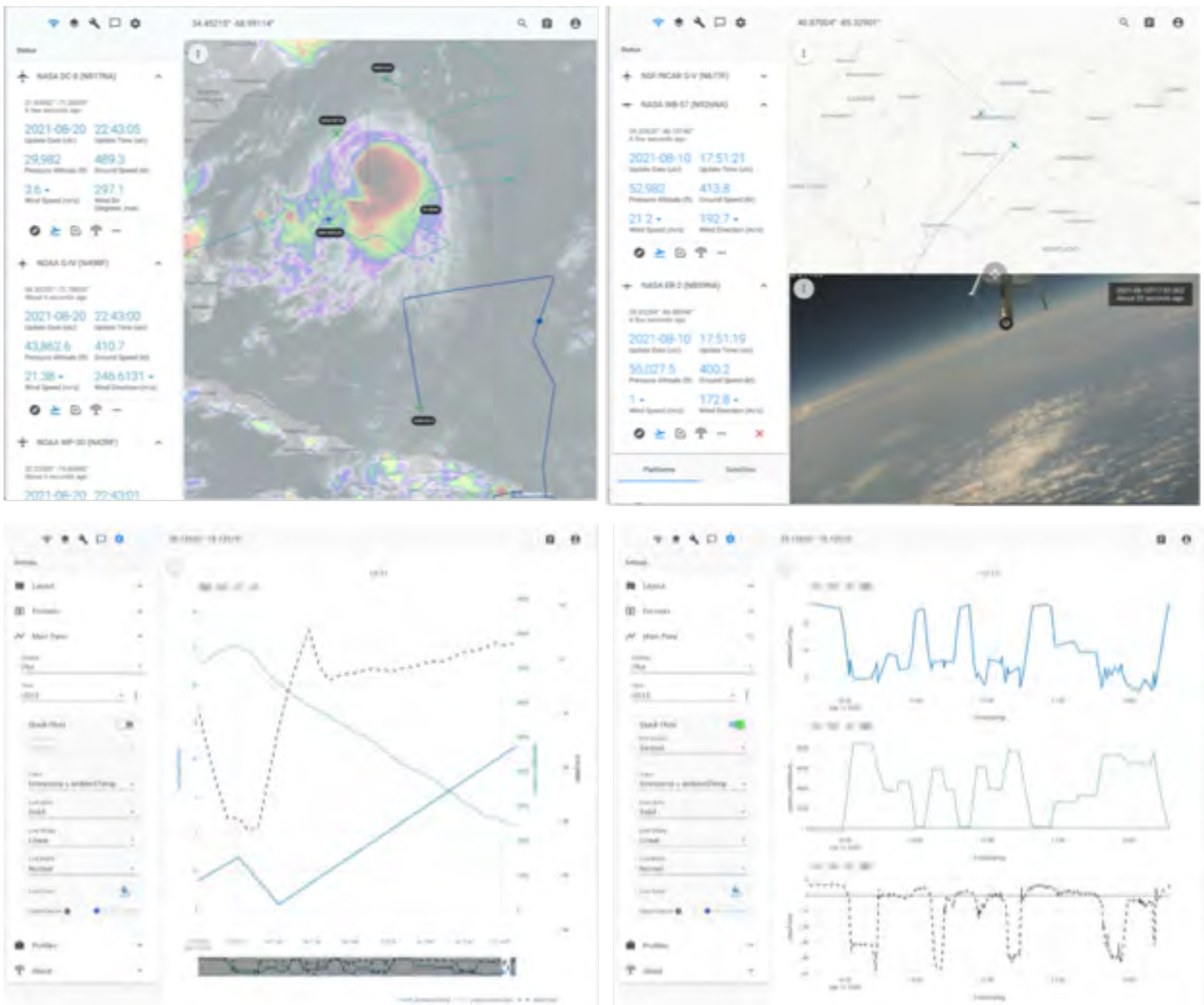


Figure 61. *The MTS mission monitor provides users with many customization and display options. Users can view multiple panes simultaneously to visualize the scientific airspace and monitor key operational information based on their project role.*

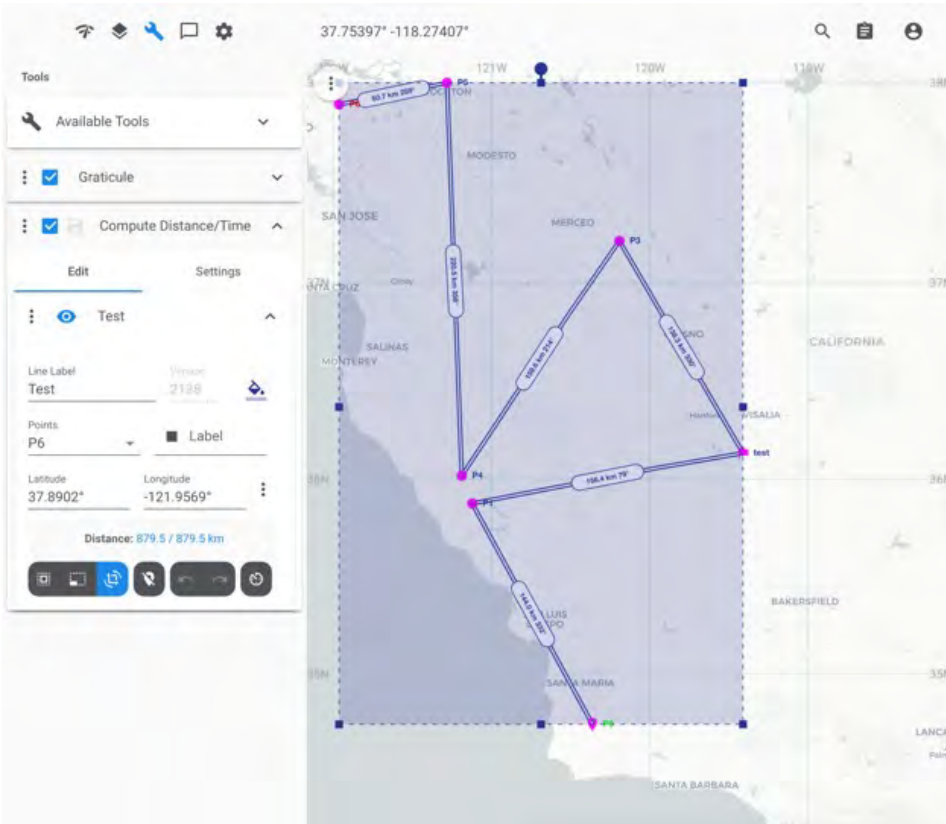


Figure 62. *Screenshot showing the new Distance/Time tool interface with the point transformation interface, simplifying coordinate transformation and point adjustments with resize and rotation options.*

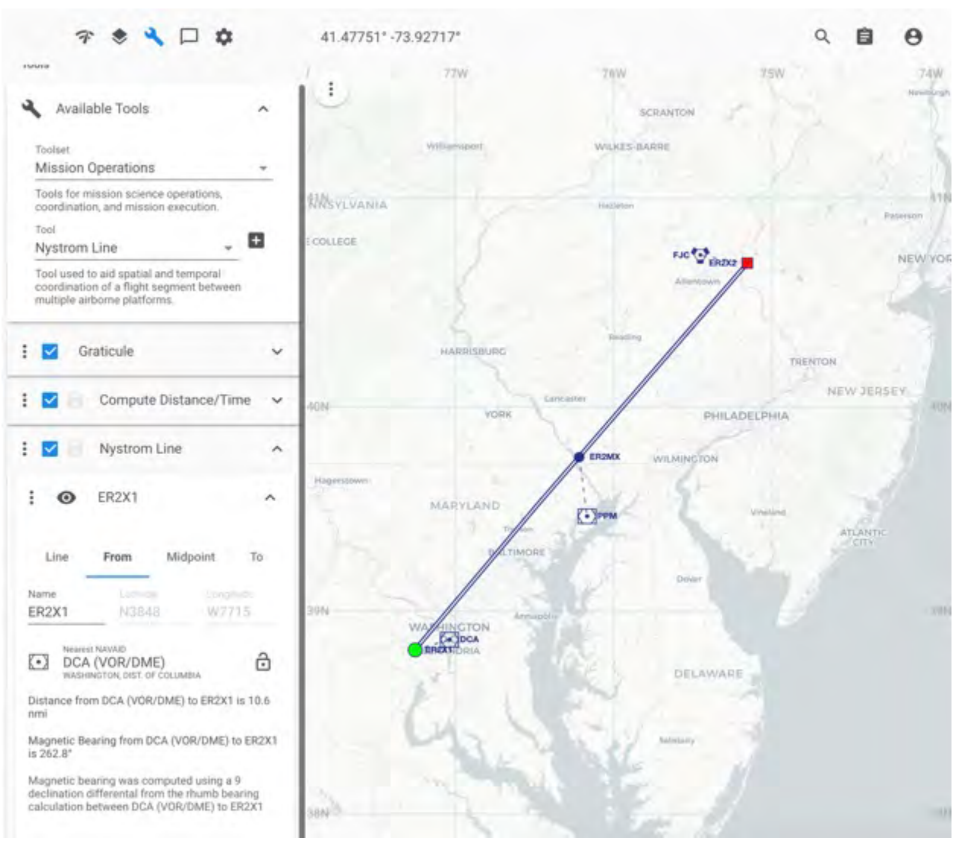


Figure 63. *Screenshot showing the new Nystrom Line tool. The tool assists mission coordinators with making rapid adjustments when planning science flight segments involving multiple airborne platforms.*

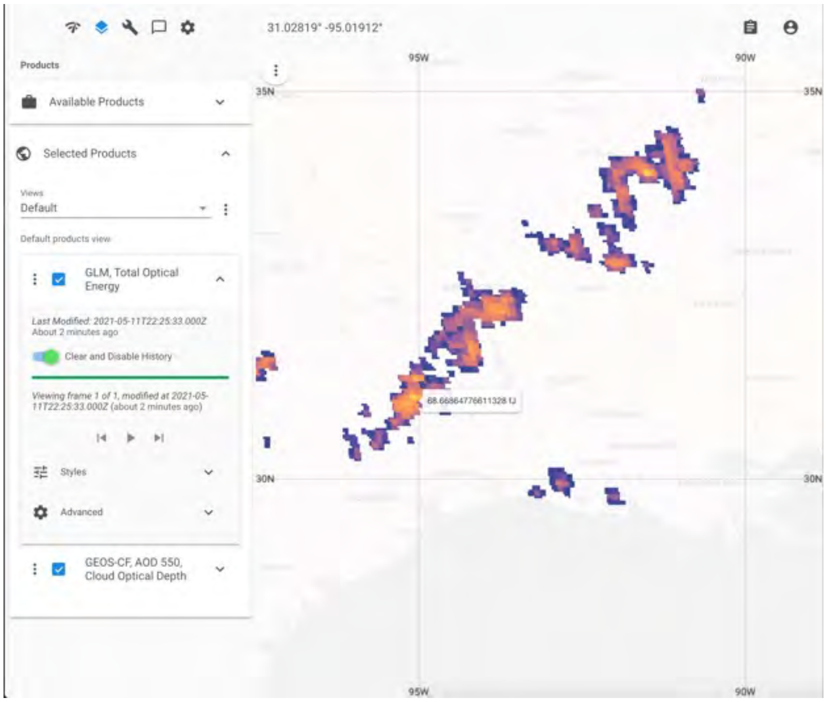


Figure 64. *Screenshot showing GLM real time lightning data. The new tool assists mission coordinators with making rapid adjustments when planning science flight segments involving multiple airborne platforms.*

The platform 3D models and other resources will soon be downloadable directly from the Airborne Science website. In addition to providing a collection of 3D rendered images, the MTS team will also make the raw 3D model files available. These files are useful for post-mission visualization, instrument development, and a variety of other applications, such as utilizing 3D resources for presentations and stakeholder communication. The Microsoft Power Point™ application, for example, makes it very simple to add a 3D (.glb) file to a slide and then rotate a camera around the 3D object for a presentation. This can be very useful to instrument teams, mission leads, and aircraft teams when communicating specifics about a mission payload, aircraft modification, or instrument detail. Check the airborne science website for more information or contact the MTS team for further details.

Figure 65. *The Mission Tool Suite provides 3D models of ASP aircraft.*

6. Advanced Planning

The ASP maintains and operates a diverse fleet of aircraft and infrastructure that support a varied and evolving stakeholder community. ASP leadership conducts a yearly strategic planning activity to ensure the program maintains currently required capabilities, renews these assets, and, as new technologies become available, extends the observational envelope to enable new Earth science measurements. The program also plans strategically through formal meetings to discuss lessons learned following all major campaigns.

ASP asset and service requirements are collected and communicated through the program flight request system (http://airbornescience.nasa.gov/sofrs), annual 5-year schedule update, and ongoing discussions with Mission and Program managers and scientists.

ASP strategic planning is focused on:

- ASP-supported (Core) Aircraft – maintenance, upgrades, determining future composition of the fleet
- Cross-cutting Infrastructure Support – support for ASP-supported and other NASA aircraft (e.g., providing tracking tools for all Earth science missions)
- Observatory Management – improved tools for managing assets and requirements while improving the service to science investigators
- New Technology – bringing new technologies to observational challenges, including application of advanced telemetry systems, on-board data processing, IT mission tools, and new platforms
- Educational Opportunities

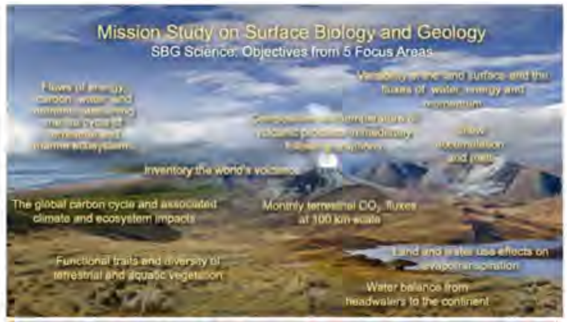
Needs Assessment Update

ASP personnel monitor upcoming Earth science space missions for potential airborne needs to support:

- Algorithm development
- Instrument test
- Calibration and validation activities
- Process studies

Surface Biology and Geology (SBG) Example

- Program Scientist: Woody Turner
- Launch date: ~2027
- Science objectives: global time series of changes in vegetation, land surface, land cover, snow, water
- Candidate payloads: VSWIR Hyperspectral imager, Thermal imager
- Representative airborne Instruments: AVIRIS, AVIRIS-NG, MASTER, PRISM, LVIS, HyTES



Past and planned airborne support:

- Western Diversity Time Series (WDTS) on the ER-2 – 7 year time series of imaging spectroscopy data;
- "Hyspiri Hawaii" – volcanoes and ocean experiment
- Expectation for high altitude and low altitude post-launch spectroscopy for classification assistance
- Zenith pointing radiometers may be needed to aid in atmospheric correction (connection with AOS?)
- **Issues:** ER-2 availability with WB-57 and GV as back-up;
- **Unmet needs**: Repeat loiter capability for high temporal time series imaging spectroscopy

Related Aircraft Calendar

- 2021 AVIRIS-NG Europe flies on B-200
- 2021, 22, 23 WDTS flies on ER-2
- 2022 SHIFT campaign in Southern California
- 2022, 23 ABoVE flies on UAVSAR (G-III) and B-200 (AVIRIS-ng)
- 2022-23 BioSCape flies on G-V and G-III
- Date TBD SBG pre-launch, a/c TBD
- Dates TBD post-launch SBG underflights, a/c TBD

Figure 66. *Quad charts have been developed to illustrate support for missions in development.*

In recent years, much attention has been focused on planning for satellite and ISS Earth Science mission, such as those previously defined in the Program of Record (POR), Earth Venture Program, and 2017 NRC Decadal Survey report. This includes the soon-to-be-launched TEMPO, SWOT, and NISAR, and the upcoming PACE missions. The Designated Observable missions under development on the basis of the Decadal Survey, along with Incubation studies and Explorer missions, are beginning to drive the future needs for airborne support. The AOS mission, for example, has a mandatory suborbital component to complement the space observations. The SBG mission team makes use of airborne data for algorithm development.

The updated ASP Needs Assessment report is currently in draft form and focuses on those future missions. New Quad charts have been developed as briefing materials to show how ASP is prepared to support those missions. An example is shown in Figure 66.

ASP also continues to support existing space missions (e.g., A-Train satellites), as well as other "foundational" missions, such as Calipso, GPM, OCO-2, and ICESat-2. Once launched, these missions require mandatory cal/val, often making use of airborne capabilities. New space missions on the International Space Station, several small satellites, and collaborations with NOAA, ESA, and other space agencies are also targets for airborne support.

NASA Earth Science launch schedule including Decadal Survey Designated Observable missions

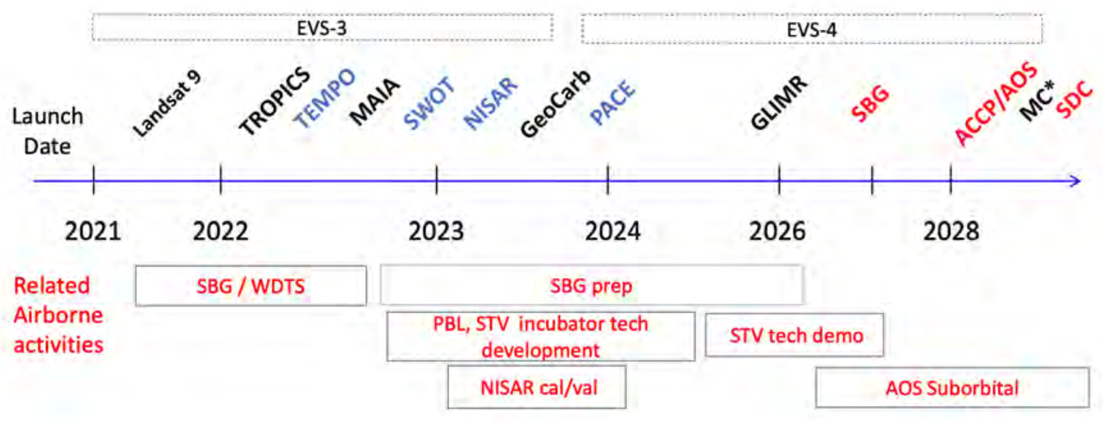


Figure 67. *The Designated Observable missions will need airborne support.*

In 2021, ASP personnel participated in science team meetings and program reviews to collect requirements information (Table 16).

Table 16. *Activities supporting ASP requirements information gathering.*

Activity
Remote participation in ESTO Forum
Remote participation in Ocean Color workshop
Remote participation in NASA Earth Science Division community workshops
Remote participation in STV Community workshop
Remote participation in PACE Applications Workshop
Remote participation in ACCP Community Forum
Remote participation in SBG Community workshop
Remote participation in SDC Study Update session
Remote participation in SMD Town Hall
Remote participation in Fourth Federal UAS Workshop
Remote participation in Fall Tactical Fire Remote Sensing Advisory Committee meeting
Remote participation in Fall 2020 and 2021 AGU Town Halls, science sessions, and poster sessions

Five-year Plan

The ASP Program maintains a 5-year plan for out-year planning and scheduling. Significant maintenance periods for the various aircraft are indicated. A copy in Appendix 1 depicts plans by science area and aircraft platform. The 5-year plan is also available on the ASP website. A snapshot of potential flight campaigns for the Decadal Survey Designated Observable and Incubation Study missions is shown in Figure 68.

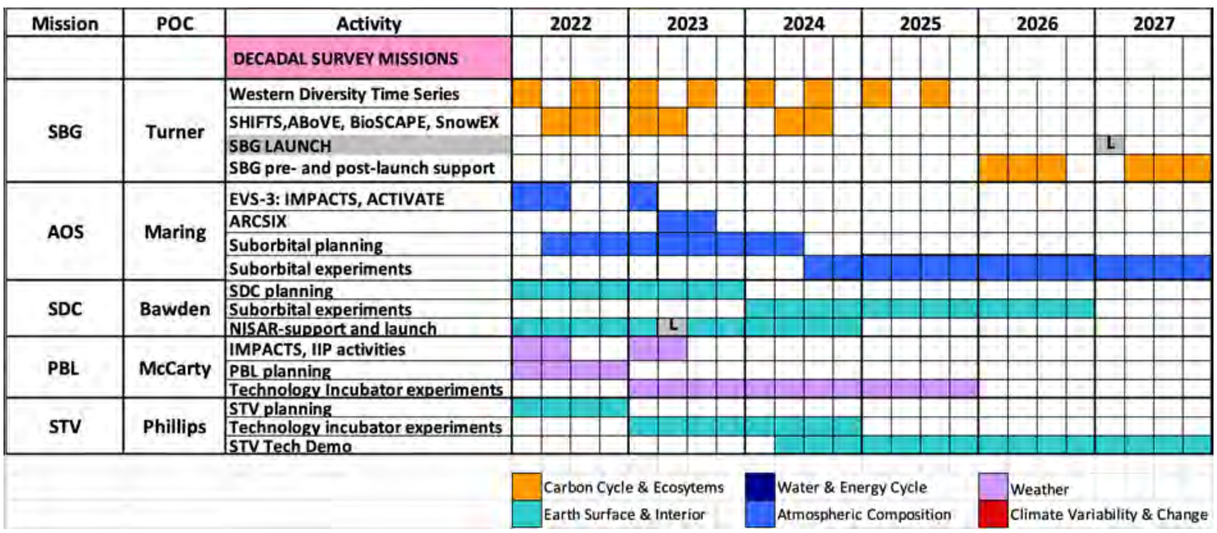


Figure 68. *Forecasted ASP support for missions identified in the 2017 Decadal Survey.*

7. Education, Training, Outreach, and Partnerships

Student Airborne Research Program 2021

The 13th annual NASA SARP took place June 14 through August 12 as an online program. From 2009-2019, SARP has competitively selected a group of approximately 30 undergraduate STEM majors from across the United States for a summer internship experience in NASA Earth science research that included flights on a NASA research aircraft. In 2020 and 2021, with COVID-19-related travel and social distancing restrictions still in place, SARP was unable to fly, but the internship continued with at-home data collection, as well as the analysis of previously collected aircraft, ground, and satellite data. Finally, the program was able to bring many students from both the

Figure 69. *The SARP intern class of 2021 took whole air samples and aerosol measurements near their homes while participating in the program online.*

2020 and 2021 classes to Palmdale for science flights on the DC-8 in December 2021.

To provide the 2020 and 2021 SARP interns with a hands-on research experience in atmospheric science, as well as to better understand the unique environmental impacts of the pandemic, SARP leadership designed an at-home air sampling project to take advantage of the geographic distribution of interns across the U.S. The Rowland/Blake Laboratory at the University of California (UC) Irvine (where SARP is typically based following student flights on the research aircraft at AFRC) provided over 1,500 air canisters to send to 2020 and 2021 SARP interns, mentors, and faculty at their homes.

In 2021, canisters were mailed out to SARP participants in April before the official start of the program in June so students could sample the air to compare with similar samples taken by the SARP 2020 class during the height of pandemic shutdowns in April 2020. These canisters will be analyzed in the UC Irvine laboratory for nearly 100 compounds, including greenhouse gases, such as methane and carbon dioxide, vehicular exhaust gases, and gases related to industrial activities.

In addition to the at-home air sampling project, SARP 2021 students are also collecting aerosol optical depth and particulate matter measurements at home through a collaboration with Citizen-Enabled Aerosol Measurements for Satellites (CEAMS) – a NASA-funded program at Colorado State University.

The majority of the internship time was spent developing individual research projects using the SARP airborne dataset from previous SARP flights, as well as data from other NASA airborne, satellite, and ground stations. The twenty-eight SARP 2021 participants each developed an individual research project in one of four research focus groups (ocean biology, terrestrial ecology, atmospheric sampling, and aerosols). They were supported by a team of faculty advisors, NASA scientists, and graduate student research mentors. Students worked with their advisors daily online and also interacted with them socially through shared online meals, group meetings, lectures, and other enrichment activities.

Figure 70. *Map showing locations of the 2021 SARP students.*

At the conclusion of the program in August, each student delivered a 12-minute AGU conference-style oral presentation on the results of their individual research project. Through the incredible efforts of Dr. Emily Schaller, the students still received a true research experience in NASA Earth and airborne science, even though the program was completely online during the summer. Dr. Schaller, who directed the SARP program for many years, has moved on to a new opportunity.

The new SARP Director, Dr. Brenna Biggs, a former SARP participant, has successfully continued the efforts of the SARP program by managing the science flights on the DC-8 in December, 2021. At that time, both the SARP 2020 and SARP 2021 classes traveled to Palmdale for science flights aboard the NASA DC-8. Fifty-three students from nearly 30 U.S. states, along with their seven graduate student research mentors and five faculty mentors, participated. All participants were fully vaccinated and followed strict health guidelines.

The payload for the flights included UC Irvine Whole Air Sampling (WAS), instruments from GSFC (ISAF, CAFÉ, Picarro, ROZE, and CANOE), aerosols instruments (LARGE and CAPS), as well as instruments from the University of Houston that measure ozone, NO, and NOx.

The mission, which spanned six flights over four days, fulfilled a variety of science objectives: measuring Los Angeles, CA air quality via missed approaches, sampling the Central Valley agricultural and oil field emissions, providing validation data over a TCCON site, making in situ gas and particle measurements over the Salton Sea, the Imperial Valley, and over the crowded harbor in Long Beach.

SARP participants were given a rare behind-the-scenes look at the instrument installation, flight planning, and scientific data collection that is the basis of every successful Earth science airborne campaign carried out by NASA. Each student had the opportunity to participate in at least three flights. During the flights, students actively engaged with instrument operators, flight crew, and onboard mission scientists, and assisted in collection of atmospheric chemistry data.

Figure 71. *SARP students from the 2020 and 2021 intern classes were able to fly science flights in December 2021.*

Appendices

Appendix A

5-year Plan

5-year plan by Science Area

Title	Flt Hours	PS/PE/PM	Related Satellite/Sensor	
1) Atmospheric Composition and Chemistry				
1.1) SABRE		Jucks		WB-57
1.2) ACCLIP	140	Jucks	AURA	WB-57
1.3) TEMPO LAUNCH		Lefer	TEMPO	
1.4) AEROMMA	200	Lefer	GOER-R, TEMPO, SNPP	DC-8
1.5) GOTHAMM-AQ	80	Lefer EPA	TEMPO	G-III (2)
1.6) STAQS	100	Lefer	TEMPO, Sentinel 5P	NASA GV
1.7) ARCSIX	300	Maring/Markus	ICESat-2	NASA GV; DC-8
1.8) Asia-AQ (4SE Asia locations)	150	Lefer / Jucks	GEMS, TROPOMI	DC-8; NASA GV
1.9) PACE LAUNCH		Lorenzoni	PACE	
1.10) PACE PAX	100	Lorenzoni, Maring	PACE	ER-2
1.11) MAIA LAUNCH		Lefer	MAIA	
1.12) GEOCarb LAUNCH		Jucks	GEOCarb	
1.13) GEOCarb cal/val (AJAX?)	??	Jucks	GEOCarb	TBD
1.14) Africa-AQ	150	Lefer		NASA GV; DC-8

Title	Flt Hours	PS/PE/PM	Related Satellite/Sensor	
6) Weather and Atmospheric Dynamics				
6.1) CPEX-CV	100	McCarty	ADM / GPM	DC-8
6.2) GOES-R cal/val	100	McCarty	GOES-R	ER-2
6.3) Planetary Boundary Layer technology and characterization experiments		ESTO	PBL incubator	DC-8; Any Twin Otter
6.4) AOS Suborbital prep		Maring	AOS	TBD

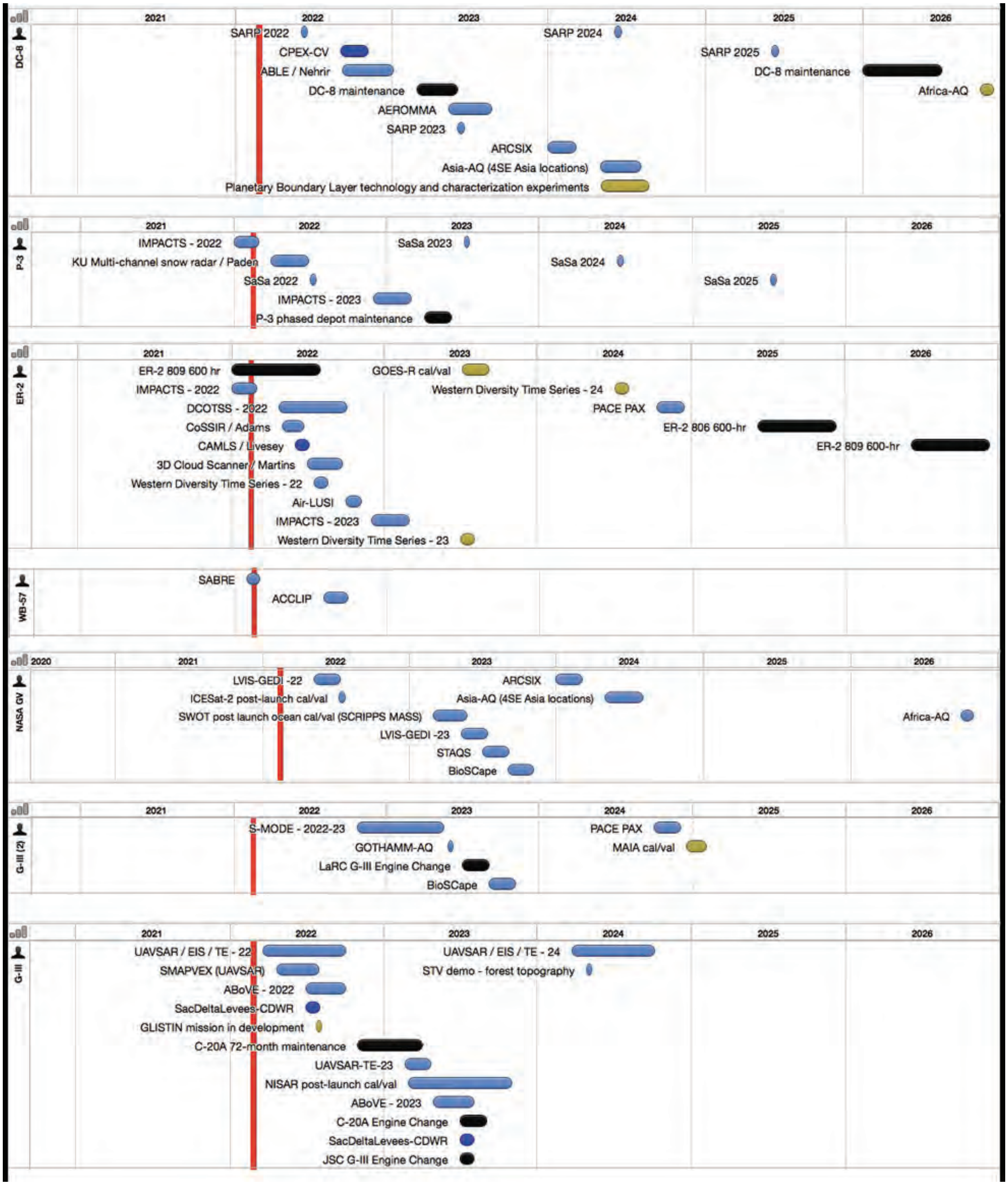
Title	Flt Hours	PS/PE/PM	Related Satellite/Sensor	
2) Carbon Cycle & Ecosystems Science				
2.1) UAVSAR-TE-22	20	Bawden/Margolis	NISAR	G-III
2.2) SHIFTS	20	Turner	SBG	Other B-200
2.3) BLUEFLIX (CMS)	150	Hibbard		Other B-200
2.4) AVIRIS-NG-22	20	Turner/Margolis	SBG	Other B-200
2.5) LVIS-GEDI -22		GSFC	GEDI	NASA GV
2.6) G-LiHT Sensor fusion	TBD	Margolis	Landsat 8	A90
2.7) ABoVE - 2022	30	Margolis	NISAR, OCO-2, ICESat 2	G-III; Other B-200
2.8) Western Diversity Time Series - 22	30	Turner	SBG	ER-2
2.9) Air-LUSI	6	Lorenzoni		ER-2
2.10) NISAR LAUNCH			NISAR	
2.11) UAVSAR-TE-23	20	Bawden/Margolis	NISAR	G-III
2.12) BLUEFLIX (CMS) - 23	150	Hibbard		Other B-200
2.13) AVIRIS-23	20	Turner/Margolis	SBG	Other B-200
2.14) ABoVE - 2023	30	Margolis	NISAR, OCO-2, ICESat2	G-III
2.15) LVIS-GEDI -23		Margolis	GEDI	NASA GV
2.16) Western Diversity Time Series - 23	30	Turner	SBG	ER-2
2.17) BioSCape	250	Turner	SBG, BioMASS	NASA GV; G-III (2)
2.18) SHIFTS - repeat	20	Turner	SBG	Other B-200
2.19) BLUEFLIX (CMS) - 24	150	Hibbard		Other B-200
2.20) STV demo - forest topography		Margolis/Phillips	STV	G-III
2.22) PACE LAUNCH			PACE	
2.23) PACE PAX		Lorenzoni	PACE	G-III (2)
2.24) SBG Pathfinder	30	Turner	SBG	TBD
2.25) Arctic COLORS	100	Lorenzoni		TBD
2.26) GLIMR cal/val		Lorenzoni	GLIMR	TBD

5-year plan by Science Area (continued)

Title	Flt Hours	PS/PE/PM	Related Satellite/Sensor	2020–2026
3) Climate Variability and Change / Cryospheric Science				
3.1) ICESat-2 post-launch cal/val	50	Markus	ICESat 2	NASA GV
3.2) Arctic Salinity mission SASSIE	60	Shiffer	SMAP	DC-3
3.3) SWOT Launch			SWOT	
3.4) NISAR LAUNCH		Bawden	NISAR	
3.5) SWOT post launch ocean cal/val (SCRIPPS MASS)	120	Shiffer	SWOT	NASA GV
3.6) SWOT post-launch hydrology cal/val (AirSWOT)	120	Shiffer	SWOT	B-200 D
4) Water and Energy Cycle				
4.1) SoOpSAR SNOW	40	Entin		Any Twin Otter
4.2) SMAPVEX (PALS)	100	Entin / Bawden	SMAP	DC-3
4.3) SMAPVEX (UAVSAR)		Bawden	NISAR	G-III
4.4) SnowEX - 23	75	Entin	GCOM-W1, GPM, SBG	Other B-200
4.5) SWOT Launch			SWOT	
4.6) SWOT post-launch hydrology cal/val (AirSWOT)	120	Shiffer/Entin	SWOT	B-200 D
4.7) SLAP support for PBL		Entin	PBL	Other B-200
4.8) PACE LAUNCH			PACE	
4.9) PACE-coastal water quality mission		Entin/Lorenzoni	PACE	TBD

Title	Flt Hours	PS/PE/PM	Related Satellite/Sensor	2020–2026
5) Earth Surface & Interior				
5.1) UAVSAR / EIS / TE - 22	150	Bawden; Phillips	NISAR	G-III
5.2) UAV demo - mission in development		Phillips		TBD
5.3) GLISTIN mission in development		Bawden		G-III
5.4) NISAR LAUNCH			NISAR	
5.5) NISAR post-launch cal/val	100	Bawden	NISAR	G-III
5.6) STV Tech Demo		Phillips	STV	TBD
5.7) UAVSAR / EIS / TE - 24	150	Bawden; Phillips	NISAR	G-III

5-year plan by Aircraft



Appendix B

Acronyms

A

ABoVE	Arctic-Boreal Vulnerability Experiment
AC3	Axial Cyclone Cloud water Collector
ACCLIP	Asian summer monsoon Chemical and Climate Impact Project
ACTIVATE	Aerosol Cloud Meteorology Interactions over the Western Atlantic Experiment
ADAHRS	Attitudes and Heading Reference System
ADS-B	Automatic dependent surveillance – broadcast
AFRC	Armstrong Flight Research Center
AGU	American Geophysical Union
AIRO	Aircraft In-Situ Radio Occultation
AirSWOT	Airborne Surface Water and Ocean Topography
AITT	Airborne Instrument Technology Transition
AJAX	Alpha Jet Airborne Experiment
ALADIN	Atmospheric Laser Doppler Instrument
AMPR	Advanced Microwave Precipitation Radiometer
AOS	Atmospheric Observing System
API	Application Programming Interface
APL	Applied Physics Laboratory
ARC	Ames Research Center
ARINC	Aeronautical Radio, Incorporated
ARMD	Aeronautics Research Mission Directorate
ASAR	Airborne Synthetic Aperture Radar
ASF	Airborne Sensor Facility
ASM	Asian Summer Monsoon
ASP	Airborne Science Program
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATM	Airborne Topographic Mapper
AVIRIS, AVIRIS-NG	Airborne Visible/Infrared Imaging Spectrometer, AVIRIS-next generation

AWAS	Advanced Whole Air Sampler
AXCTD	Airborne Expendable Conductivity Temperature Depth

B

BAERI	Bay Area Environmental Research Institute
BAS	British Antarctic Survey
BBR	Broadband Radiometers
BGAN	Broadband Global Area Network
BLUEFLUX	Blue Carbon Prototype Products for Mangrove Methane and Carbon Dioxide Fluxes

C

CAFÉ	Compact Airborne Formaldehyde Experiment
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
Cal/val	Calibration / Validation
CAMBOT	Continuous Airborne Mapping by Optical Translator
CANOE	Compact Airborne NO_2 Experiment
CAPS	Cloud, Aerosol, and Precipitation Spectrometer
CARCAH	Chief, Aerial Reconnaissance Coordination, All Hurricanes
CARE	Cabin Altitude Reduction Effort
CAS	Commercial Aviation Services
CBM	Conditions-Based Maintenance
CDP	Cloud Droplet Probe
CEAMS	Citizen-Enabled Aerosol Measurements for Satellites
CH_4	methane
Chi-WIS	Chicago Water Isotope Spectrometer
CHIME	Copernicus Hyperspectral Imaging Mission for the Environment
CMIS	Compact Midwave Imaging System
CO	Carbon monoxide
CO_2	Carbon dioxide
COA	Certificate of Authorization
CONUS	Continental USzzz

CPDLC	Controller Pilot Data Link Communications
CPI	Cloud Particle Imager
COLD 2	Carbon Oxide Laser Detector 2
COMA	Carbon Monoxide Measurement & Analysis
COVID	Coronavirus Disease
CPEX-AW	Convective Processes Experiment – Aerosols & Winds
CRS	Cloud Radar System
CVI	Counterflow Virtual Impactor
CY	Calendar Year

D

DAWN	Doppler Aerosol WiNd
DCOTSS	Dynamics and Chemistry of the Summer Stratosphere
DGPS	Differential GPS
DLH	Diode Laser Hygrometer
DLR	German Aerospace Agency
DMS	Digital Mapping System
DO	Designated Observable
DOE	Department of Energy (U.S.)
DPOPS	DCOTSS Portable Optical Particle Spectrometer

E

ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
eMAS	Enhanced MODIS Airborne Simulator
EOS	Earth Observing System
ESA	European Space Agency
ESD	Earth Science Division
ESPO	Earth Science Project Office
ESSP	Earth System Science Pathfinder
ESTO	Earth Science Technology Office
EV, EVS-2, EVS-3	Earth Venture, Earth Venture Suborbital-2, Earth Venture Suborbital-3

F

FAA	Federal Aviation Administration
FCDP	Fast Cloud Droplet Probe
FIREX-AQ	Fire Impacts on Regional Emissions and Chemistry Experiment – Air Quality
FLIR	Forward Looking Infrared
FR	Flight Request
FY	Fiscal Year

G

GCAS	GeoCAPE Airborne Simulator
GEO-CAPE	GEOstationary Coastal and Air Pollution Events
GEDI	Global Ecosystem Dynamics Investigation
G-LiHT	Goddard's Lidar, Hyperspectral and Thermal
GLM	Geostationary Lightning Mapper
GOES-R	Geostationary Operational Environmental Satellite - R
GPM	Global Precipitation Mission
GPS	Global Positioning System
GRC	Glenn Research Center
GSA	General Services Administration
GSFC	Goddard Space Flight Center

H

H_2O	water
HAL	Harvard Halogen Instrument
HALE	High altitude long endurance
HALO	High Altitude Lidar Observatory
HAMSR (HAMSR)	High Altitude Monolithic Microwave integrated Circuit (MMIC) Sounding Radiometer
HCNO	Fulminic acid
HSRL	High Spectral Resolution Lidar
HUPCRS	Harvard University Picarro Cavity Ring Down Spectrometer
HWV	Harvard Lyman-α Photofragment Fluorescence Hygrometer
HYPPOS	HyperMapping with Hyperspectral Precise Pointing Optical Sensor
HyTES	Hyperspectral Thermal Emission Spectrometer

I

ICESat	Ice, Cloud, and land Elevation Satellite
ICOS	Integrated Cavity Output Spectroscopy
IIP	Instrument Incubator Program
IMPACTS	Investigation of Microphysics and Precipitation for Coast-Threatening Snowstorms
IMU	Inertial measurement unit
InSAR	Interferometric Synthetic Aperture Radar
IR	Infrared
IRIG-B	Inter-range instrumentation group - B
ISAF	In situ Airborne Formaldehyde
ISRO	Indian Space Research Organization
ISS	International Space Station
IT	Internet technology
IWGADTS	Interagency Working Group for Airborne Data and Telecommunication Systems

J

JPL	Jet Propulsion Laboratory
JSC	NASA Johnson Space Center

K

L

LARGE	Langley Aerosol Research Group Experiment
LaRC	Langley Research Center
LIAISE	Land surface Interactions with the Atmosphere over the Iberian Semi-arid Environment
LiDAR	Light Detection and Ranging
LIF-NO	Laser Induced Fluorescence – Nitrogen Oxide
LIF-SO2	Laser Induced Fluorescence – Sulphur Dioxide
LTER	Long Term Ecological Research
LVIS	Land, Vegetation, and Ice Sensor

M

MAGIC	Monitoring of Atmospheric composition and Greenhouse gases through multi-Instruments Campaigns
MAIA	Multi-Angle Imager for Aerosols
MAS	MODIS Airborne Simulator
MASS	Modular Aerial Sensing System
MASTER	MODIS/ASTER Airborne Simulator
MC	Mass Change
METAR / TAF	Aviation Routine Weather Report / Terminal Aerodrome Forecast
MMS	Meteorological Measurement System
MODIS	Moderate Resolution Imaging Spectroradiometer
MOOSE	Michigan Ontario Ozone Source Experiment
MOSES	Multiscale Observing System of the Ocean Surface
MSFC	Marshall Space Flight Center
MTS	Mission Tools Suite
MURI	Multi-band Radiometer
MVIS	Miniature Video Imaging System

N

NAMA	North American Monsoon Anticyclone
NASDAT	NASA Airborne Science Data and Telemetry
NAST-I	National Polar-orbiting Operational Environmental Satellite System Airborne Sounder Testbed - Interferometer
NAVO	Naval Oceanographic Office
NISAR	NASA-ISRO SAR
NO, NO_2	Nitrogen Monoxide, Nitrogen Dioxide
NOAA	National Oceanographic and Atmospheric Administration
NRC	National Research Council
NSRC	National Suborbital Research Center

O

OCO-2	Orbiting Carbon Observatory - 2
OMG	Oceans Melting Greenland
OSU	Oregon State University

P

PACE	Plankton, Cloud, and ocean Ecosystem
PALMS	Particle Analysis By Laser Mass Spectrometry
PBL	Planetary Boundary Layer
PDM	Programmed Depot Maintenance
PI	Principal Investigator
PICARD	Pushbroom Imager for Cloud and Aerosol R&D
PIF	Payload Information Form
PMD	Palmdale Airport
POS	Position and Orientation Systems
PRISM	Portable Remote Imaging Spectrometer

Q

R

R&A	Research and Analysis
ROZE	Rapid Ozone Experiment
RSP	Research Scanning Polarimeter

S

S-MODE	Submesoscale Ocean Dynamics and Vertical Transport
SABRE	Stratospheric Aerosol processes, Budget, and Radiative Effects
SAFIRE	French facility for airborne research
SAR	Synthetic Aperture Radar
SARP	Student Airborne Research Program

SASSIE	Salinity and stratification at the Sea Ice Edge
SatCom	Satellite Communications
SBG	Surface Biology and Geology
SBIR	Small Business Innovative Research
SDC	Surface Deformation and Change
SEO	sensor equipment operator
SHARC	SCIFLI Hayabusa 2 Airborne Re-entry Observation Campaign
SHIFTS	SBG High Frequency Time Series
SIERRA	Sensor Integrated Environmental Remote Research Aircraft
SIO	Scripps Institute of Oceanography
SLAP	Scanning L-band Active Passive
SMAP	Soil Moisture Active Passive
SMD	Science Mission Directorate
SMOS	Soil Moisture and Ocean Salinity
SnowEx	Snow Experiment
SOFRS	Science Operations Flight Request System
SP2	Single Particle Soot Photometer
STEM	Science Technology Engineering and Math
STV	Surface Topography and Vegetation
SWE	Snow Water Equivalent
SWOT	Surface Water and Ocean Topography

T

TCEQ	Texas Commission on Environmental Quality
TEMPO	Tropospheric Emissions: Monitoring Pollution
TOLNet	Tropospheric Ozone Lidar Network
TRACER-AQ	Tracking Aerosol Convection Interactions Experiment – Air Quality
TROPOMI	Tropospheric Monitoring Instrument
TOIL	Twin Otter International Limited
TCCON	Total Carbon Column Observing Network

U

UAS	Unmanned Aircraft System, Uncrewed Aerial System
UAV	Unmanned Aerial Vehicle
UASO3	UAS Ozone
UAVSAR	Uninhabited Aerial Vehicle Synthetic Aperture Radar
UC	University of California
UCATS	UAS Chromatograph for Atmospheric Trace Species
UCLA	University of California Los Angeles
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
USVI	U.S. Virgin Islands
UTLS	Upper Troposphere / Lower Stratosphere
UTLS-AMP	Upper Troposphere / Lower Stratosphere Aerosol Microphysics Package
UV	Ultra-violet

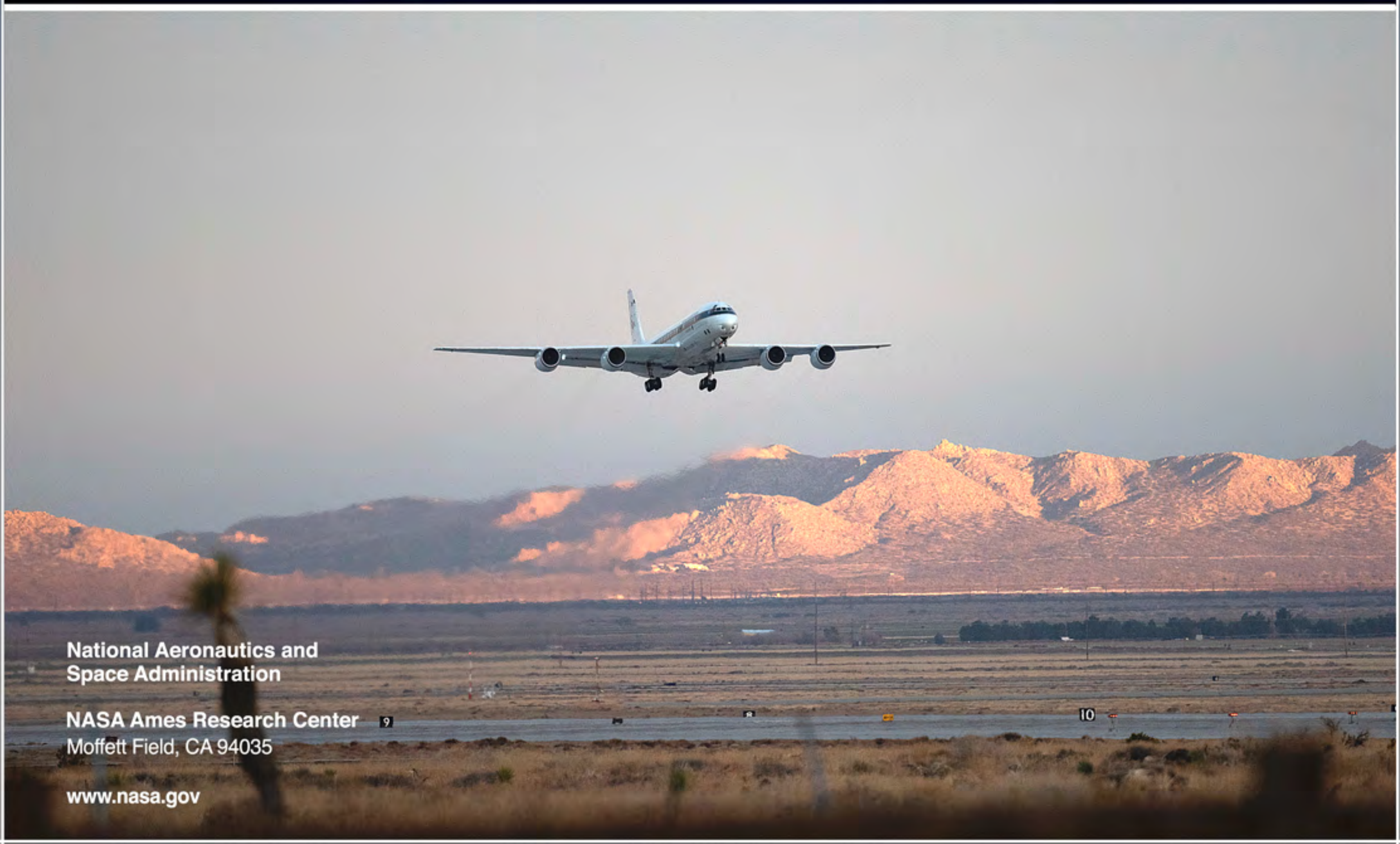
V

VHF	Very High Frequency
VIPR	Vapor in-cloud Profiling Radar
VSWIR	Visible to Short wave infrared

W

WAS	Whole Air Sampler
WDTS	Western Diversity Time Series
WFF	Wallops Flight Facility
WHOI	Woods Hole Oceanographic Institute

XYZ



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NASA Ames Research Center
Moffett Field, CA 94035

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