National Aeronautics and
Space Administration

2015
UPDATE ON NASA AIRBORNE SCIENCE PROGRAM (ASP) REQUIREMENTS

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ABSTRACT

Earth Science requirements for airborne capabilities vary dramatically with regard to aircraft flight regimes (altitude and range), duration, and payload carrying capacity, along with many operational characteristics. This report updates the known requirements for NASA Airborne Science support from earlier reports, including the "NASA Airborne Science Program Requirements 2013 Update." A special section is devoted to lessons learned from the Earth Venture Suborbital requests. This report also includes results from a survey of NASA Science Center requirements. This report is a combined product, documenting requirements for the next 5 years and focusing on capability needs and gaps for the Airborne Science Program.

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EXECUTIVE SUMMARY

The NASA Airborne Science Program (ASP) serves the Earth Science community with a wide range of aircraft, instrument and mission support capabilities. Earth Science requirements for airborne capabilities vary dramatically between science disciplines and from instrument to instrument. NASA researchers require access to highly modified aircraft covering very different flight regimes with regard to altitude and range, duration, and payload carrying capacity, onboard power and satellite communications. For ASP to continue to meet the science community it is crucial to understand the requirements as far into the future as possible in order to schedule maintenance, upgrades, acquisitions, and divestments.

This report describes the current and projected needs of the NASA SMD Earth Science community with information collected from planned NASA satellite mission teams, Research and Analysis Programs, and technology development programs, in addition to flight requests, discussions with Program scientists and scientists at the NASA science centers.

Current aircraft performance capabilities are represented in the Figures ES-1 and ES-2 below. The NASA ESD / ASP program-funded aircraft include the DC-8, P-3, two ER-2s, C-20 (Gulfstream-III), and a Global Hawk. This requirements activity shows demand for all the ASP-funded aircraft and many others. Apparent gaps in platform capabilities are shown in Figure ES-3, based on activities underlying this report.

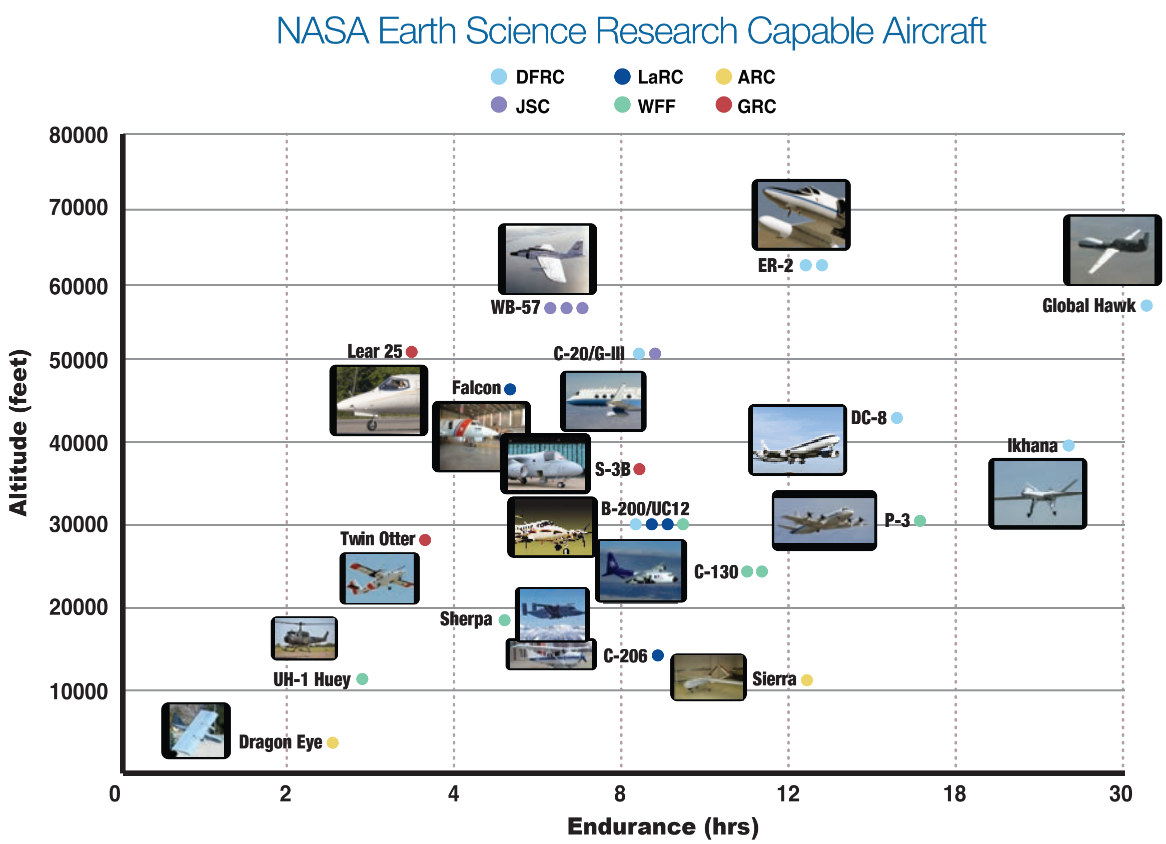


Figure ES-1 *NASA Research Aircraft characterized by altitude and endurance capability.*

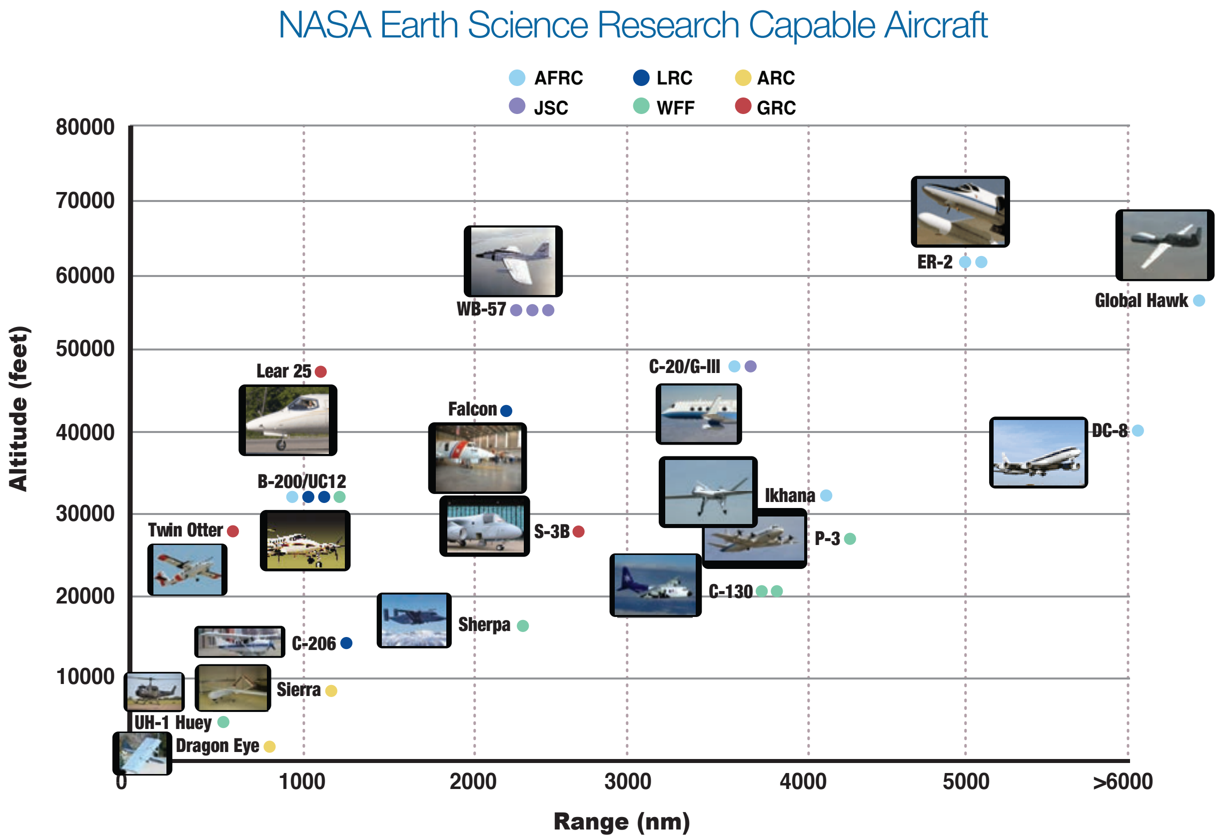


Figure ES-2 *NASA Research Aircraft characterized by altitude and range capability.*

Findings:

- *There are clear requirements for all aircraft currently in the core fleet given currently funded instrument development, satellite missions, R&A research, and the Earth Venture line of missions.*
- *All satellite missions currently in formulation have plans to use aircraft during one or more phases of their development and operations.*
- *Requirements for medium altitude- medium payload, business-class jet or Super King Air aircraft have increased and represent a gap in the current fleet, forcing projects to rely on less capable aircraft, or other agency aircraft.*
- *There are no platforms capable of providing low altitude long endurance measurements required for ocean and land surface fluxes and radiation measurements.*
- *There is a continued call from the science community for high altitude long endurance platforms for providing geostationary-like measurements in addition to providing diurnal measurements of atmospheric phenomenon.*

Figure ES-3 highlights some gaps identified in the existing fleet based on feedback from currently funded Programs and Projects and Table ES-1 explains the need behind each of these gaps. (In Figure ES-3, the terminology "core-funded" refers to the Earth Science Directorate subsidy to these assets in the ASP fleet. The JSC G-III aircraft was only subsidized through FY 2014.)

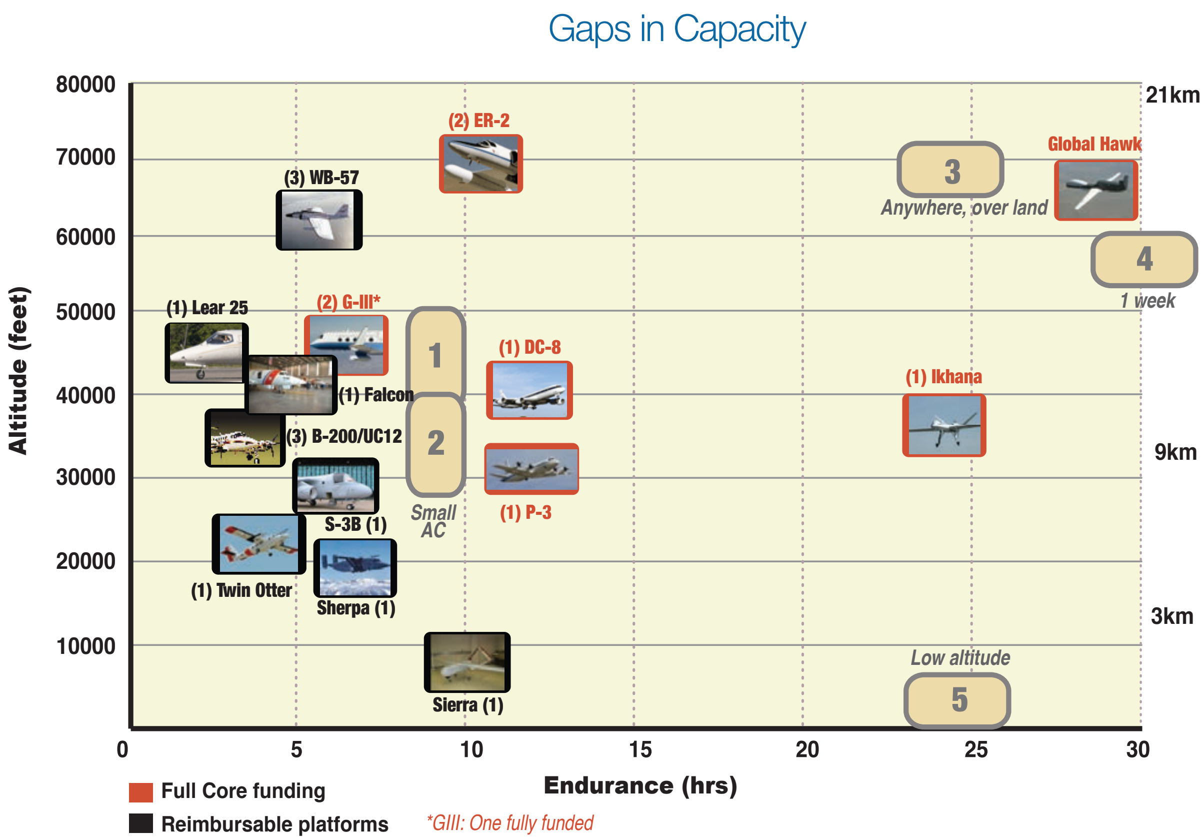


Figure ES-3 *Summary of aircraft gaps as identified by NASA Science Center Survey.*

Table ES-1 Explanation of gaps indicated in Figure ES-3

	Gap	Performance Need	Science Rationale	Possible Solution
1	Flight altitude to 50kft, 8 hr duration, moderate payload	Similar to DC-8 flight regime, including nadir ports, but something smaller and less expensive	Lidar systems for weather and terrain mapping, but not full size laboratory	Gulfstream V
2	Flight altitude 25 to 35 kft, 8 hr duration, small to moderate payload	Similar to King Air (B-200), but with longer duration	In situ sampling and ocean color both want 8 hrs, but flight characteristics and cost of B-200	King Air B-350; possible business jet
3	Very high altitude (65+kft), long duration (24 hrs), fly anywhere	Similar flight regime as Global Hawk, ideally higher, not constrained to over ocean	Ability to see the evolution of atmospheric transport processes during a 24-hour period	Continue UAS in the NAS work; possible new aircraft
4	Very long endurance (~week)	Above weather and traffic with ability to follow event	Ability to monitor or track fire or pollutant plume, storm development	Aerial refueling, airship or balloon; new aircraft
5	Low altitude, long duration (or long range to target), where the target is remote or there are basing constraints	100 – 200 ft over water, stable flight; over land with auto pilot	Radiation science over the ocean; carbon flux measurement; coral or ocean color imaging	Long duration, low altitude UAS (OR ship launch)

1. INTRODUCTION

Objectives and Background

The NASA Airborne Science Program charter is to meet the needs of the NASA Earth Science community by operating and maintaining a fleet of highly modified aircraft capable of enabling observations in support of NASA satellite missions and associated research and analysis programs. The purpose of this report is to document the planned and projected aircraft capabilities required by the NASA Science Mission Directorate (SMD) Earth Science Division (ESD) and serves as an update to a previous report. This report addresses the latest information based on discussions with Earth scientists in the NASA community, program scientists at NASA HQ, science teams for current and upcoming Earth science spacecraft missions, and science teams for upcoming field missions. It also draws on the data in the Science Operations Flight Request System (SOFRS), although flight requests tend to be more near-term and based on what aircraft systems are currently available.

The goal of this report is both to document current requirements and to provide guidance on changes needed to ensure that the ASP aircraft fleet and associated aircraft continue to serve NASA Earth science. Another objective is to identify mission support needs that require investment, as in integration infrastructure, data handling or communications systems.

Scope

This report addresses the many capabilities of the Airborne Science Program that together provide science investigators with the services and performance needed for their missions. These include:

- *Aircraft systems, both manned and unmanned, with a wide spectrum of flight altitudes, ranges, and speeds. Flight planning and deployment planning.*
- *Payload carrying capabilities, including weight and volume, power, environmental control, specialized access ports, windows and probes. Pods and dispensers.*
- *Integration of payload systems, multiple payloads, data and communication systems. Multi-platform mission coordination.*
- *Mission tools, including real-time data access, communications, and mapping.*
- *Science support instrumentation and systems, such as cameras and inertial measurement units (IMUs).*

Approach to Data Collection

The primary method for collecting information found in this report was through direct interviews with stakeholders of the Airborne Science Program. Additional information was collected through published reports, on-line schedules, or information presented at science team meetings or mission-related workshops. All information collected from these sources was then recorded in the form of internal reports and spreadsheets, validated again by stakeholders and then synthesized and summarized in this report.

We have collected requirements information from many sources, including:

- *Existing flight requests,*
- *Aircraft flight schedules,*
- *Annual 5-yr planning forecast*
- *Recent science meeting proceedings and reports*
- *Interviews with program managers and program execs*
- *Interviews with principle investigators*
- *Earth Science satellite and space mission science teams and presentation materials*
- *Interagency science groups / documentation*
- *NASA Centers survey activity and requirements meeting*

The last item refers to survey activity that occurred in late 2012 and a review meeting which took place on April 19, 2013. The results from this activity are highlighted in this report.

Report Structure

The report is structured as follows: Section 2 summarizes the current assets of the program and includes a brief synopsis of past fleet utilization and requirements analysis efforts. (Detailed specifications of the current capabilities are included in Appendix A.) Section 3 presents known or projected requirements for Earth Science satellite and International Space Station missions, process studies including Earth Venture Suborbital missions, and technology development. A new section since the 2013 report presents airborne requirements suggested for the next National Research Council Decadal Survey, which is expected in 2017. Section 4 summarizes the activity and results of the 2013 Science Center Survey initiative, including gaps and investments identified from that activity. Section 5 presents analysis, recommendations and conclusions. Appendix B contains the most recent ASP 5-year plan. Appendix C is a list of acronyms found in the report.

2. AIRBORNE SCIENCE PROGRAM PORTFOLIO

Current Program Assets

The current composition of the NASA ASP core aircraft fleet is driven by on-going demand by funded projects and programs for each platform's unique capabilities. Table 1 lists the current aircraft portfolio of the program including non-SMD-funded aircraft at NASA centers that are modified to carry instrumentation. The science community also has access to numerous other platforms from commercial providers and through cooperation with the Interagency Coordinating Committee for Airborne Geoscience Research and Applications (ICCAGRA), as discussed in Appendix A.

In addition to aircraft, the program maintains facility instrumentation associated with each vehicle to provide basic aircraft and environmental parameters, Iridium and Inmarsat satellite communications systems, onboard data systems, and processing hardware. In addition, the program maintains and customizes several software systems integral to the function of the program and supported missions. The ASP website provides the user community with information on all platforms, including experimenter's handbooks, flight schedules and engineering support. The website also provides the primary interface to the Science Operations Flight Request System (SOFRS), which enables users to scope missions, develop cost estimates, track flight hours and review flight reports. The Mission Tools Suite (MTS) provides a customizable common operating picture for airborne science missions, with a moving maps display showing the location of mission aircraft along with relevant geospatial data products, and it the primary interface during a mission for viewing instrument status and realtime data products. All assets and capabilities of the Airborne Science Program are detailed in Appendix A.

Table 1. Current NASA Aircraft Platforms

Airborne Science Program Resources	Platform Name	Center	Duration (Hours)	Useful Payload (lbs)	GTOW (lbs)	Max Altitude (ft)	Airspeed (knots)	Range (Nmi)	Internet and Document References
ASP Supported Aircraft*	DC-8	NASA-AFRC	12	30,000	340,000	41,000	450	5,400	http://airbornescience.nasa.gov/aircraft/DC-8
	ER-2 (2)	NASA-AFRC	12	2,550	40,000	>70,000	410	>5,000	http://airbornescience.nasa.gov-/aircraft/ER-2
	Gulfstream III (G-III)(C-20A)	NASA-AFRC	7	2,610	69,700	45,000	460	3,400	http://airbornescience.nasa.gov-/aircraft/G-III_C-20A_-_Dryden
	Global Hawk	NASA-AFRC	26	1,500	26,750	65,000	335	9,000	http://airbornescience.nasa.gov-/aircraft/Global_Hawk
	P-3	NASA-WFF	14	14,700	135,000	32,000	400	3,800	http://airbornescience.nasa.gov-/aircraft/P-3_Orion
Other NASA Aircraft	B-200 (UC-12B)	NASA-LARC	5	2,000	13,500	28,000	220	1,000	http://airbornescience.nasa.gov-/aircraft/B-200_UC-12B_-_LARC
	B-200	NASA-AFRC	5	1,700	13,420	28,000	270	1,400	http://airbornescience.nasa.gov-/aircraft/B-200_-_DFRC
	B-200	NASA-LARC	5	2,000	13,500	28,000	220	1,000	http://airbornescience.nasa.gov-/aircraft/B-200_-_LARC
	B-200 King Air	NASA-WFF	6.0	1,800	12,500	28,000	275	1,800	https://airbornescience.nasa.gov-/aircraft/B-200_King_Air_-_WFF
	C-130 (2)	NASA-WFF	12	36,500	155,000	33,000	290	3,000	https://airbornescience.nasa.gov-/aircraft/C-130_Hercules
	C-23 Sherpa	NASA-WFF	6	7,000	27,100	20,000	190	1,000	http://airbornescience.nasa.gov-/aircraft/C-23_Sherpa
	Cessna 206H	NASA-LARC	5	646	3,600	10,000	150	700	http://airbornescience.nasa.gov-/aircraft/Cessna_206H
	Cirrus SR22	NASA-LARC	6.1	932	3,400	10,000	175	970	http://airbornescience.nasa.gov-/aircraft/Cirrus_Design_SR22
	Dragon Eye	NASA-ARC	<1	1	6	1000	34	3	http://airbornescience.nasa.gov-/aircraft/B-200_-_LARC
	Gulfstream III (G-III)	NASA-JSC	7	2,610	69,700	45,000	460	3,400	http://airbornescience.nasa.gov-/aircraft/G-III_-_JSC
	HU-25C Falcon	NASA-LARC	4.5	2,000	32,000	36,000	350	1,600	http://airbornescience.nasa.gov-/aircraft/HU-25C_Falcon
	Ikhana	NASA-AFRC	20	2,000	10,500	45,000	171	3,000	http://airbornescience.nasa.gov-/aircraft/Ikhana
	Learjet 25	NASA-GRC	2	2,000	15,000	45,000	350	1,000	http://airbornescience.nasa.gov-/aircraft/Learjet_25
	Learjet 35	NASA-GRC	4	4,200	19,600	45,000	350	2,300	
	S-3B Viking	NASA-GRC	6	12,000	52,500	40,000	350	2,300	http://airbornescience.nasa.gov /aircraft/S-3B
	SIERRA	NASA-ARC	10	100	400	12,000	60	600	http://airbornescience.nasa.gov-/platforms/aircraft/sierra.html
	T-34C	NASA-GRC	3	100	4,400	25,000	150	500	http://airbornescience.nasa.gov-/aircraft/T-34C
	Twin Otter	NASA-GRC	3	3,000	11,000	25,000	140	450	http://airbornescience.nasa.gov-/aircraft/Twin_Otter_-_GRC
	UH-1	NASA-WFF	2	3,880	9,040	12,000	108	275	https://airbornescience.nasa.gov-/aircraft/UH-1_Huey
	Viking-400 (4)	NASA-ARC	11	100	520	15,000	60	600	https://airbornescience.nasa.gov-/aircraft/Viking-400
	WB-57 (3)	NASA-JSC	6.5	8,800	72,000	60,000+	410	2,500	http://airbornescience.nasa.gov-/aircraft/WB-57

Historical ASP Fleet Utilization

Historical data on aircraft flight hours can be used as a guide to future demand for the ASP fleet. Shown in Figure 1 are total program flight hours for the past 16 years. The total has grown significantly in recent years, especially with Operation IceBridge and Earth Venture-1 activities. This trend is expected to continue, especially with the recent release of the Earth Venture Suborbital-2 solicitation.

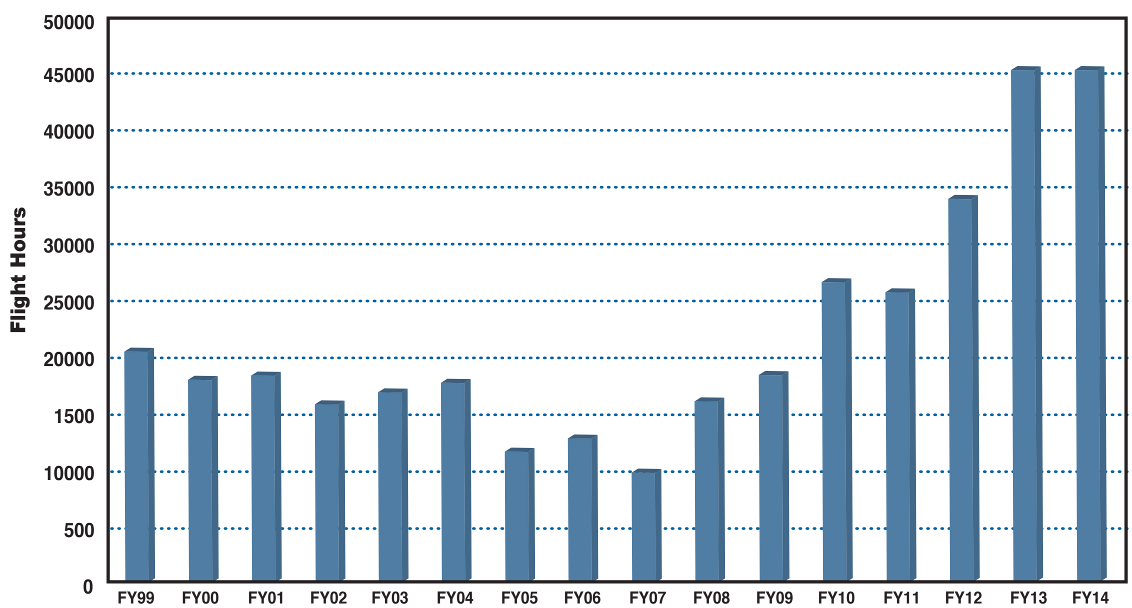


Figure 1. *Airborne Science Flight hours. Hours in FY2013 and FY2014 exceed 4500.*

Shown in Table 2 is the composition of the flight hours across the fleet for 2014. Table 3 shows historical data since 2006. Note that the majority of the flight hours are for the ASP program-supported aircraft, including especially the use of the Gulfstream – III carrying the UAVSAR instrument. This trend is anticipated to continue for the foreseeable future. A parallel trend is the steady use of other capability, readily available commercially or from other agency providers.

Table 2. Flight hours by Aircraft in FY 2014

Aircraft	Total FRs	Total Approved	Total Partial	Total Completed	Total Hours Flown
DC-8	8	6	0	5	88.8
ER-2	25	18	8	7	359.8
P-3	13	6	0	4	610.2
WB-57	9	7	2	5	46.1
Twin Otter	31	17	3	13	509.7
B-200	13	9	1	7	352.4
G-3	48	31	0	27	771.6
Global Hawk	7	3	0	3	444.7
C-130 Hercules	2	2	1	1	231
C-23 Sherpa	6	4	1	2	316
Dragon Eye	1	0	0	0	0
Falcon - HU-25	4	2	0	2	69.2
S-3 Viking	1	1	0	1	37
SIERRA	4	0	0	0	0
T-34	2	1	0	1	29.2
Other	32	16	1	11	734.4
TOTALS	**206**	**123**	**17**	**89**	**4600.1**

Table 3. Flight hours (per FY) for major Aircraft since 2006

Aircraft / Hrs flown	2006	2007	2008	2009	2010	2011	2012	2013	2014
DC-8	264	292.1	104.8	20.3	650.8	228.3	533.1	474.5	88.8
ER-2	168	148.9	190.4	150.7	188.8	143.7	443.2	566.8	359.8
P-3	123	201.4	250.9	216.1	112.1	533.3	410.2	462.3	610.2
G-III	-	155.9	0	526	278.8	448.4	623.8	890.5	771.6
Global Hawk	-	-	-	0	227.3	0	219.8	517.3	444.7
WB-57	122	11.3	83.8	44.5	40	79.7	29.7	0	46.1
B-200	157	415.7	55	331.8	274.6	304.5	157.2	258.3	352.4
Twin Otter	199	327.4	171.7	103.8	292.1	281.6	429.2	150.7	509.7
Sherpa	-	-	-	-	-	0	257.9	320.1	316
SIERRA	-	0	-	76	10	17	31.6	5.8	0
Falcon	-	-	-	-	-	-	75.5	31.9	69.2
Cessna 206	-	0	-	41	18.3	87.2	99.3	0	0
C-130 Hercules	-	-	-	-	-	-	-	2	231
T-34	-	0	-	26.4	73.7	0	37.6	35.1	29.2
Ikhana	-	54.5	79.1	0	0	0	0	0	0
Learjet 25	-	4.1	-	66.7	14.6	0	0	0	0
Aerosonde	74	11	23.5	0	-	-	-	-	-
Altair	73	98.4	-	-	-	-	-	-	-
S-3 Viking	-	-	-	-	-	-	-	-	37
Other	108	40.1	-	273.4	523.1	363.7	539.7	868.6	734.4
TOTALS	**1288**	**996.1**	**1634.8**	**1876.7**	**2704.2**	**2605.4**	**3887.8**	**4583.9**	**4600.1**

3. REQUIREMENTS FOR EARTH SCIENCE

Given the fleet of platforms and their capabilities as described previously, the question to the scientist is: does this range of capabilities meet your science needs? Since NASA Earth Science covers many topics, the range of observation and measurement requirements is also very broad. From past, current and future requirements activities, it is possible to describe and draw the general science regimes for airborne performance. The spectrum covers a wide range of altitude, duration, range and payload capability. Figure 2 is a science overlay in altitude – endurance space, based on ten years of combined data points from science community studies, including the "Suborbital Science Missions of the Future." Figure 3 is based on more recent input.

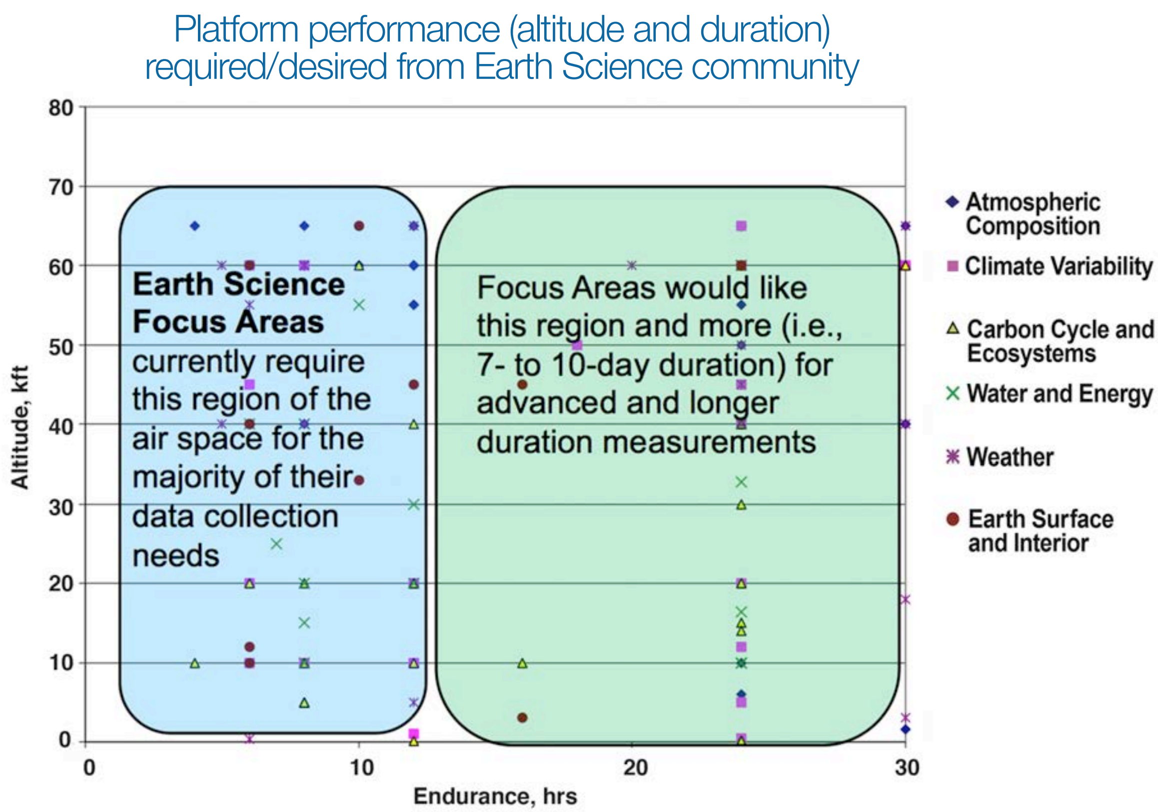


Figure 2. *Science overlay – requirements in altitude-duration space for Earth Science focus areas. (Data from ASP science database.)*

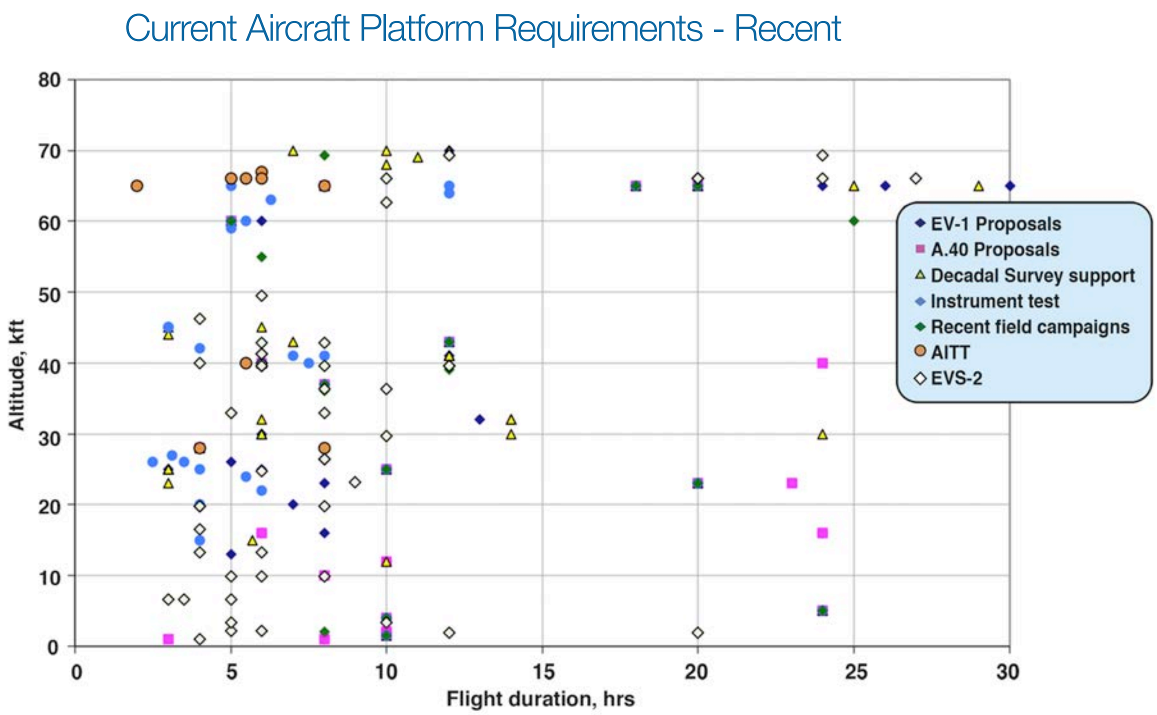


Figure 3. *Requirements derived from recent studies.*

Definitions and Requirements

This section describes the science regimes and the science motivation for platform performance. In general, a balanced portfolio of low, medium, and high altitude aircraft will be needed to operate, test and evaluate advanced instruments and mission design concepts. The general definitions below also imply that a useful payload can be carried while flying at altitude for the duration of the flight.

Very High Altitude (>60,000 ft) High Altitude (>45,000 ft) – Enables testing instrument retrievals and assessment. High-altitude, multi-payload, stable flight platform (e.g., ER-2, WB-57) for precise satellite under flights

Mid Altitude (20,000 – 45,000 ft) – Medium- to large-size aircraft are cost effective, capable platforms for correlative studies with ground sensors, low aircraft and satellites. Long-duration, long-range, mid-altitude aircraft (e.g., P-3, DC-8) to deploy in situ, lidar and polarimeter instruments for atmosphere and ocean/atmosphere interface studies, with both profiling and constant altitude legs

Low Altitude (<20,000 ft), Very low altitude (<5000 ft) – small to mid-size aircraft (e.g., B-200) for deploying in situ and remote sensors to validate retrievals; also larger aircraft (e.g., C-23 Sherpa) for carrying larger payload at low altitude.

High altitude flight is required for simulation of satellite / space missions because the observations are made from above most of the atmosphere. Furthermore, the environmental conditions simulate space if the payload is not in a controlled space. High altitude is also desirable for atmospheric measurements at the tropopause and in the stratosphere. Note that higher levels of instrument autonomy, similar to spacecraft payloads, are required for high altitude aircraft with fewer or no operators on board.

Additional reasons for flying high:

- *Reach the very important upper troposphere/ lower stratosphere boundary (UTLS)*
- *Fly over cloud tops and over a greater depth of the cloud*
- *Simulate space environmental conditions*
- *Simulate column seen from space*
- *Simulate area coverage seen from space*
- *For a given instrument, swath width scales linearly with altitude (AGL) and pixel resolution scales inversely*
- *Air traffic control regulations change at higher altitudes (usually more lenient)*

Long endurance / long range

It is still not possible to completely sample the troposphere (45-50 kft) with in situ sensors on board a single aircraft without compromising on either payload or ceiling. In general, longer-duration, longer-range, higher-altitude, more cost-effective aircraft are needed.

Heavy lift above 40 kft to reach the tropopause is of huge value. Heavy lift is defined as the ability to carry as many as 12 different payload instruments and can weigh from 2000 to 6000 lbs. Medium lift above 27 kft and for long duration (8 hr) is also needed. Medium lift is defined as the ability to carry up to 6 different payload instruments and can weigh from 200 to 600 lbs.

Additional reasons for long duration.

- *Diurnal (24 hrs) and longer continuous measurements are needed.*
- *Distance to remote locations often requires long duration flight to ensure that there will be sufficient time to take data.*
- *Especially needed with current technology is long-range capability to make measurements over the polar regions. Alternatively, aircraft with longer endurance that could safely operate out of the common higher-latitude airfields at desired mission tempo could satisfy the ongoing need for measurements in polar regions.*

Flying laboratory at mid-altitude

The research community still requires scientists to be onboard the aircraft in many cases. This is important for research, technology development & testing, and generally more cost effective than investing in autonomy for research operations.

The current interdisciplinary focus of Earth science requires more complex payloads, so heavy lift is still a premium (20+ instruments), although there are still questions that can be investigated with a medium sized payload (e.g., 5-10 instruments).

Also at mid-altitude is a requirement for less expensive flight opportunities for up to 8 hours, but for a smaller number of instruments. A combination of several imagers or a combination of an active and passive instrument for cal/val activities does not necessarily require heavy lift, but longer legs than a B-200.

Low altitude / long endurance

Low altitude flights are especially useful for some land surface measurements, canopy measurements, and ocean measurements. Pixel size or other measurement resolution improves with closeness to the surface. Often the regions of interest are remote - a far distance from the aircraft base and so long range is required. For some measurements, long endurance is desirable for mapping large areas without returning to base, in order to achieve a homogeneous data set within a certain time frame.

Requirements related to NASA Earth Science missions from space

The NASA Earth Science community depends for a majority of Earth Science studies on data from Earth-orbiting satellites. The Airborne Science Program supports Earth Science satellite missions in a variety of ways:

- *Algorithm development prior to launch*
- *Instrument test during the mission development phase*
- *Calibration and validation after launch*
- *Field tests that parallel the mission measurements with improved temporal or spatial specificity or resolution*
- *Observation technique development*
- *Develop an early adopters community (i.e. user ready to ingest/use data once the spacecraft becomes operational)*

A significant portion of ASP missions support or complement satellite missions. One representative example is the annual CALIPSO cal/val mission, ongoing since 2006. CALIPSO, along with CloudSat provide aerosol and cloud data from space. In 2008, the “Caribbean Validation Mission” used data from the High Spectral Resolution Lidar (HSRL) flying on the LaRC B-200 to verify the effectiveness of new daytime calibration algorithms being applied to data from the CALIOP lidar on the CALIPSO satellite. In 2009, a series of flights of the HSRL on the LaRC B-200 was flown to verify that the calibration of the CALIOP lidar on CALIPSO before and after a laser transmitter switch was made. The data from the HSRL flights proved conclusively that the calibration of the satellite instrument was not affected by the change in lasers. In 2011, HSRL participated in MACPEX, and in 2012, a new version of the HSRL, along with the Research Scanning Polarimeter (RSP), returned to the Caribbean for more CALIOP cal/val measurements. Activities during the first ever combined ship-aircraft SABOR mission also supported CALIPSO cal/val. Similar combined activities are planned.

Many other ASP flight experiments support satellites in the A-Train, including AQUA, AURA, TERRA and GPM. The Atmospheric Composition and Chemistry focus area uses field data to complement composition measurements from space, while the Weather focus area relies on measurements in severe storms to complement wind and precipitation observations. In support of ASTER and MODIS imaging products, the MASTER and MAS instruments, flying on the ER-2 and other aircraft, act as satellite simulators for numerous terrestrial ecology, fire and land use / land change studies.

Recommendations from the National Research Council's 2007 Decadal Survey drive much of the current requirements not only for Airborne Science, but also for the Earth Science Technology Office (ESTO) programs. (http://esto.nasa.gov). A recent hour-tally of support from ASP to Decadal Survey missions is shown in Figure 4. These are self-reported indications from the Principle Investigators, as to which missions their science supports. The SMAP mission, launched in January 2015, is the first of these missions to become operational. A new Decadal Survey is expected in 2017. Expectations for ASP support in the new missions is discussed in Section 3.4 of this report.

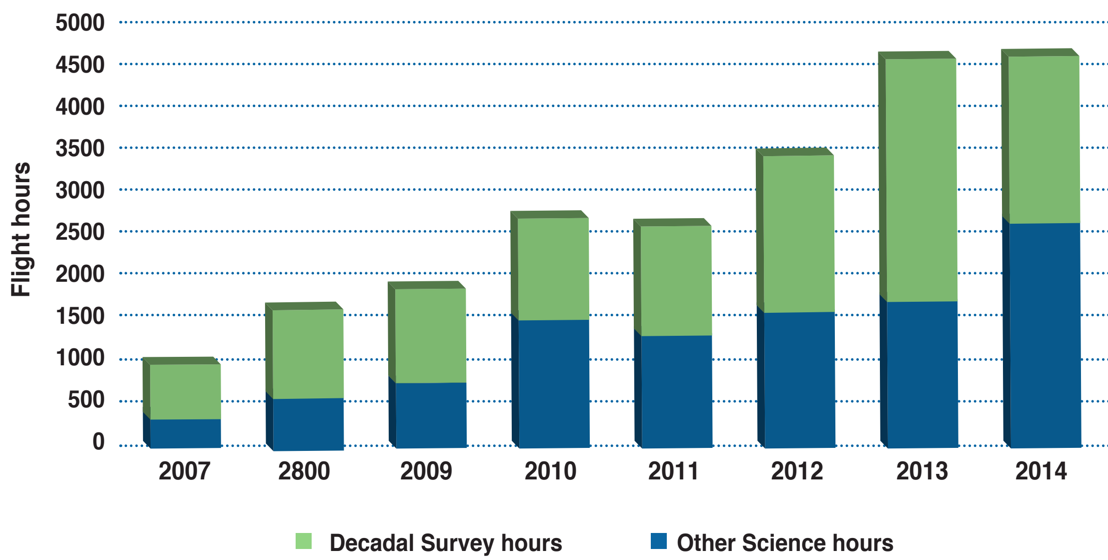


Figure 4. *Airborne flight hours in support of Decadal Survey mission preparations. (Self-reported by principle investigators.)*

[1]*NRC Decadal Survey: "Earth Science and Applications from Space: National Imperatives for the Next Decade*

Figure 5. *Earth Science Spacecraft Missions.*

Figure 5 shows the current NASA satellite mission portfolio. The following four tables indicate how the Airborne Science Program supports these missions throughout satellite mission lifecycles.

Table 4. **Airborne Science support for NASA Earth Science Space Missions in Extended Operations**

Mission	Satellite Instruments	Supporting/ related aircraft instruments	Airborne Science supporting activities	Aircraft
Aura	MLS, HIRDLS, OMI, TES	ASMLS; Discover-AQ, KORUS-AQ packages	Data product validation	ER-2, P-3, DC-8
Calipso / Cloudsat	CALIOP, IIR, WFC, CPR	HSRL, HSRL-2, AMPR, CRS, CPL	Cal/val	B-200, UC-12, ER-2
Aqua / Terra	MODIS, AMSR-E, ASTER, MISR, CERES	MAS, eMAS, MASTER, AVIRIS	Data product validation	ER-2, Twin Otter

NASA Earth Science is very proud to have launched five Earth Science missions in a twelve-month period from February 2014 through January 2015, as shown in Figure 6. These, along with several other active primary missions, are also supported by ASP in various ways, as listed in Table 5.

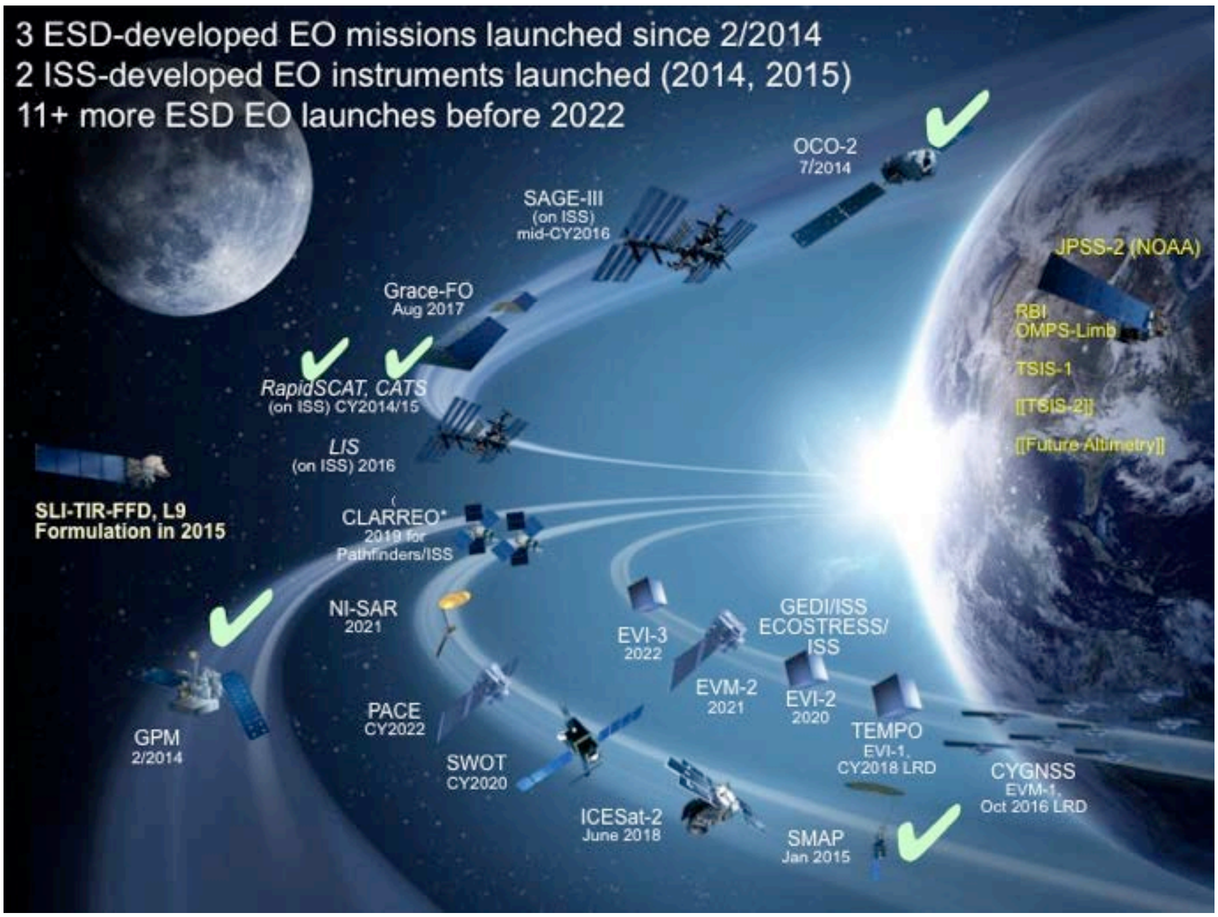


Figure 6. *NASA Earth Science missions highlighting five launched recently from February 2014 – January 2015.*

Table 5. Airborne Science support for NASA Earth Science Space Missions with Primary Operations (active missions)

Mission	Satellite Instruments	Supporting/ related aircraft instruments	Airborne Science supporting activities	Aircraft
Aquarius*	Radiometers, scatterometer	Radiometers, AESMIR, SLAP	Data product validation	P-3, B-200
GPM	Microwave Imager, Doppler Precipitation Radar (DPR)	AMPR, COSMIR, HIWRAP	Instrument calibration & Data product validation	ER-2, DC-8, Citation
OCO-2	NIR spectrometer	Picarro CO2/CH4	Instrument calibration & Data product validation	Alphajet, SIERRA
Suomi-NPP	VIIRS, CrIS, ATMS, OMPS	NAST, S-HIS, eMAS, MASTER, AVIRIS	Instrument calibration & Data product validation	P-3, Twin Otter, ER-2
Landsat-8	Spectrometer	AVIRIS, AVIRIS-ng, LVIS, UAVSAR, G-LiHT	Instrument calibration & Data product validation	ER-2, G-III, Twin Otter, DC-8, P-3
SMAP	L-band radar, L-band radiometer	UAVSAR, PALS, SLAP	Instrument calibration & Data product validation	G-III, P-3, B-200
Rapid-SCAT (ISS)	Scatterometer	Wind radar	TBD	TBD
CATS (ISS)	Lidar	CPL	Instrument calibration & Data product validation	ER-2

**Aquarius mission ended in June 2015*

Table 6. Airborne Science support for Missions in Implementation phase: near-term launches

Mission / launch date	Satellite Instruments	Supporting/ related aircraft instruments	Airborne Science supporting activities	Aircraft
ICESat-2 (2018)	Laser altimeter	OIB, MABEL, GLISTIN	Gap-filling field mission; Algorithm development,	P-3, DC-8, ER-2, B-200, G-III, GH
GRACE-FO (2017)	Advanced laser range-finding interferometer	Laser altimeter	Operation IceBridge	P-3
CYGNSS (2016) = 8 microsatellites (Ocean surface winds)	Delay Doppler Mapping Instrument	HDSS	Field data	WB-57
LIS (ISS) (2016)	Lightning monitor	Prototype LIS	Demonstration	Falcon
SAGE-III (ISS) (2016)	Solar occultation instruments; measures ozone	HSRL-2	Instrument test	B-200, ER-2

A relatively new platform for Earth Science missions is the International Space Station (ISS). As noted in Figure 7 and shown in Tables 7, below, and 8 on page 19. Some of the new and upcoming missions are destined for the International Space Station. Already the CalWater2 mission flying CPL on the ER-2 has supported cal/val of the Cloud Aerosol Transport System (CATS). Additional instrument development and cal/val activity is likely.

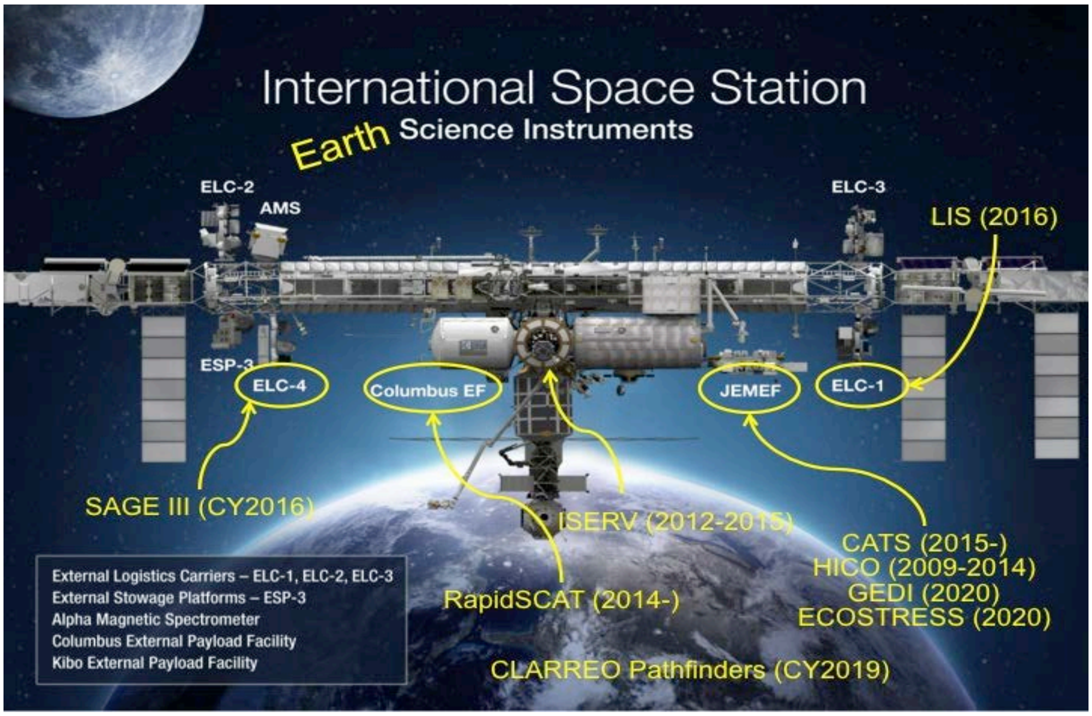


Figure 7. *Earth Science activities from the International Space Station.*

Table 7. Airborne Science support for Missions in Formulation

Mission / launch date	Satellite Instruments	Supporting/ related aircraft instruments	Airborne Science supporting activities	Aircraft
NISAR (2021)	InSAR, Lidar Ocean Color	UAVSAR	Algorithm development, Instrument calibration & Data product validation	G-III
PACE (2022)	Instument (OCI)	OCI simulator, PRISM, HSRL	Algorithm development Instrument calibration & Data product validation	Twin Otter, B-200, ER-2
SWOT (2020)	Ka-band radar, C-band radar	AirSWOT, KaSPAR, HAMSR	Algorithm development, Instrument calibration & Data product validation	B-200
TEMPO (2018)	geostationary ultraviolet visible spectrometer	GEO-TASO, GCAS	Instrument calibration & Data product validation	Falcon, UC-12
ECOSTRESS (ISS) (2020)	High resolution multispectral thermal imaging spectrometer	HYTES	Algorithm development, Instrument calibration & Data product validation	Twin Otter, ER-2
GEDI (ISS) (2020)	Lidar	G-LiHT	Algorithm development	Small plane

Table 8. Airborne Science support for Missions in Definition

Mission / launch date	Satellite Instruments	Supporting/ related aircraft instruments	Airborne Science supporting activities	Aircraft
HyspIRI	VIS-IR imaging spectrometer	AVIRIS, MASTER, AVIRIS-ng, HyTES	Algorithm development, Instrument calibration & Data product validation	ER-2, Twin Otter
ASCENDS	CO2 Lidar	CO2 lasers	Instrument development	DC-8, B-200, Twin Otter
GEO-CAPE	Hyperspectral imagers	GEO-TASO, Pan-FTS, PRISM	Instrument development,algorithm development	Falcon, Twin Otter, ER-2, WB-57
ACE	Polarimeter, Lidar, cloud radar	Polarimeters, HSRL-2, EXRAD	Instrument flight test, algorithm development	ER-2, P-3, B-200
OCO-3 (ISS)	Three high resolution grating spectrometers (measures CO2)	CO2 laser systems, such as CarbonHawk	Instrument calibration & Data product validation	Falcon, GH, AlphaJet

Active support for upcoming missions includes HyspIRI prep, which is adding a third year in 2016 for volcano and tropical imaging. AirSWOT is in active science data collection at multiple locations preparing for SWOT.

Preparation for the ASCENDS mission is focused on understanding the characteristics of several candidate CO2 sensors. A series of experiments on board the DC-8 have carried three different instruments over calibrated sites to assess performance. In 2014, these instruments also under-flew OCO-2 to collect comparative data. Future flights in 2016 and beyond are also planned to understand systematic errors of the various measurement approaches. In 2017, a flight carrying both active and passive sensors is under discussion.

Requirements related to Earth Science focus areas field and process studies, including Earth Venture Suborbital missions

Most of the requirements outlined in this section of the report are cited from the Flight Request system summary of current missions and illustrated in the ASP 5-year plan. (http://airbornescience.nasa.gov/sofrs/) Referring to the 5-year plan in the Appendix, upcoming process studies are summarized in Table 9 below. Plans for upcoming EVS-2 missions are described later in this section.

Table 9. Upcoming Field Campaigns

Mission	Objective	Location	Date	Aircraft Instrumentation	Aircraft
Operation IceBridge	Arctic and Antarctic data continuity	Greenland, Alaska, Antarctica	2015, 2016, 2017, 2018	Multiple, See notes	P-3, DC-8, ER-2, G-III, C-130, B-200, Falcon
KORUS-AQ	Air pollution monitoring	Korean peninsula	2016	Similar to DISCOVER-AQ package for air pollution	DC-8
ABoVE	Boreal land composition changes	Alaska	2017 - 2019	CARVE-like package	Low-latitude, medium-lift, TBD by solicitation
SnowEx	Snow cover extent	US, Canada	2016 - 2018	SLAP	Medium altitude, medium payload
Arctic COLORS	Coastal impacts of climate change	Alaska	TBD	Imagery, aerosols (like SABOR); PRISM	Low-to-mid altitude with moderate payload; UAS desired for river / coastal measurements
South Asia LCLUC	Land cover change / agriculture	India	TBD	AVIRIS, MASTER UAVSAR	ER-2, G-III
CAMPex	Atmospheric Composition Ex	Philippines	2019	Full radiation package	P-3
EXPORTS	Major ocean study	Southern Ocean	>2020	Complement ship and satellite measurement	TBD

In addition to Earth Venture missions described later in this section, several near-term missions dominate the ASP schedule for field campaigns. These include the continuation of Operation IceBridge, KORUS-AQ, and ABoVE.

Operation Ice Bridge (OIB), also known as IceBridge

Aircraft are providing a critically important data gap-filler for laser altimeter measurements at the poles between ICESat which ended in 2009, and ICESat-2 scheduled for launch in 2018. The multi-year Operation Ice Bridge is the largest airborne survey of Earth's polar ice ever flown and is yielding a 3-D view of the Arctic and Antarctic ice sheets, ice shelves and sea ice. IceBridge is using multiple instruments and aircraft platforms to map Arctic and Antarctic areas once each year. The workhorse aircraft for OIB have been NASA's P-3 and DC-8 aircraft, but other platforms have participated as well, including G-III, Single Otter, and ER-2 and C-130. Even as OIB continues, separate flights of the ICESat-2 simulator instrument – MABEL – are being carried out on other aircraft, including ER-2, Proteus, and B-200. The SIMPL instrument has also flown on a B-200 to make measurements in suppport of ICESat-2 algorithm development. The upcoming schedule for OIB is shown in Figure 8.

Climate Variability and Change/Cryospheric Science

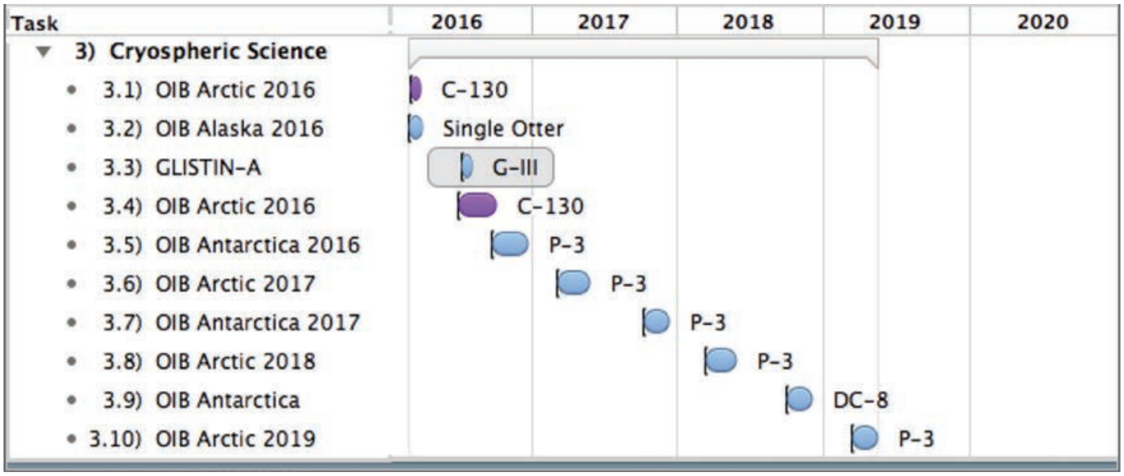


Figure 8. *Airborne support for Cryospheric Science is primarily for IceBridge*

KORUS-AQ: An International Cooperative Air Quality Field Study in Korea

KORUS-AQ offers the opportunity to advance NASA goals and those of its international partners related to air quality through a targeted field study focused on the South Korean peninsula and surrounding waters. The study, planned for the April-June 2016 timeframe would integrate observations from aircraft, ground sites, and satellites with air quality models to understand the factors controlling air quality across urban, rural, and coastal interfaces. For this field study, the NASA DC-8 was selected due to the need for a complex payload and space for collaborating Korean scientists. The complementary ocean color mission, KORUS-OC, will fly the GEO-TASO instrument on a B-200 aircraft. Note that missions in foreign airspace often require the presence of local nationals.

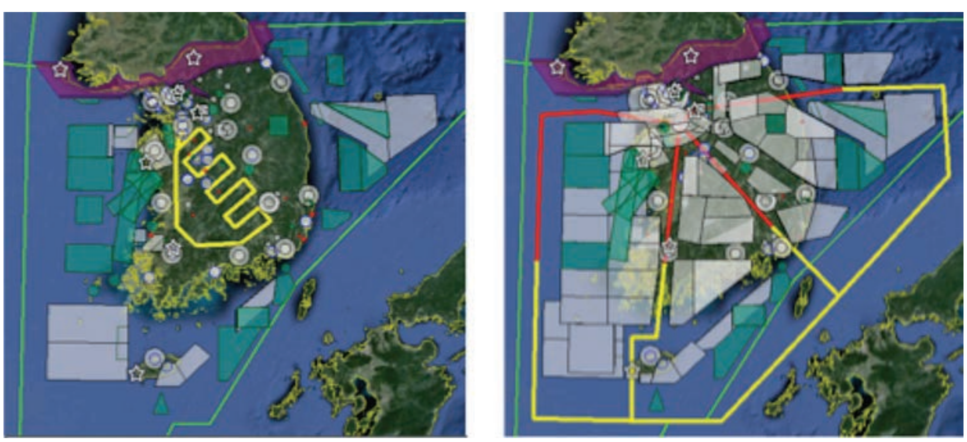


Figure 9. *Representative flight lines over the South Korean peninsula. Low altitude flight to sample surface pollution (left), and higher-altitude survey flight lines (right).*

ABoVE: The Arctic-Boreal Vulnerability Experiment

The focus of the Arctic-Boreal Vulnerability Experiment (ABoVE) field campaign is a large-scale study of ecosystem responses to environmental change in western North America's Arctic and boreal region and the implications for social-ecological systems. The study region is shown in Figure 10. The aircraft mission schedule is indicated in Figure 11, based on the 2015 ABoVE study paper. The aircraft are yet to be determined, but a payload similar to that used in the EV-1 mission CARVE is expected. The Sherpa has been held as a placeholder aircraft for ABoVE, indicating that a low-altitude, medium-lift platform is required.

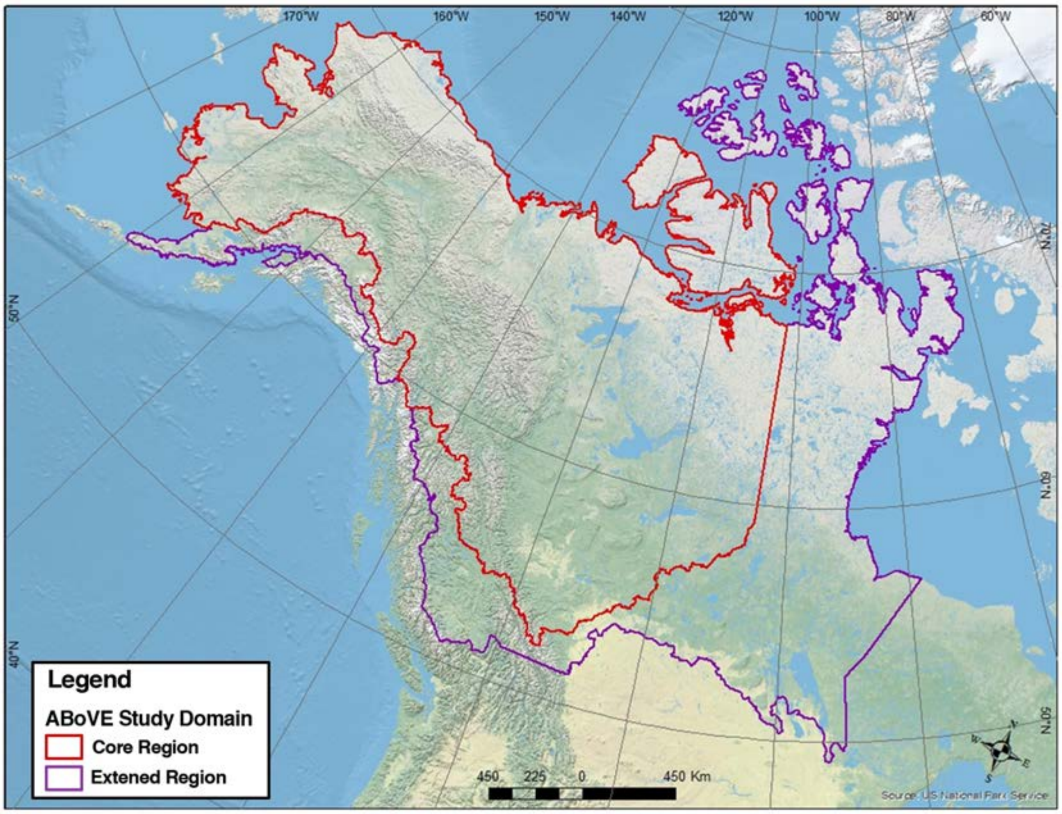


Figure 10. *ABoVE Study Area.*

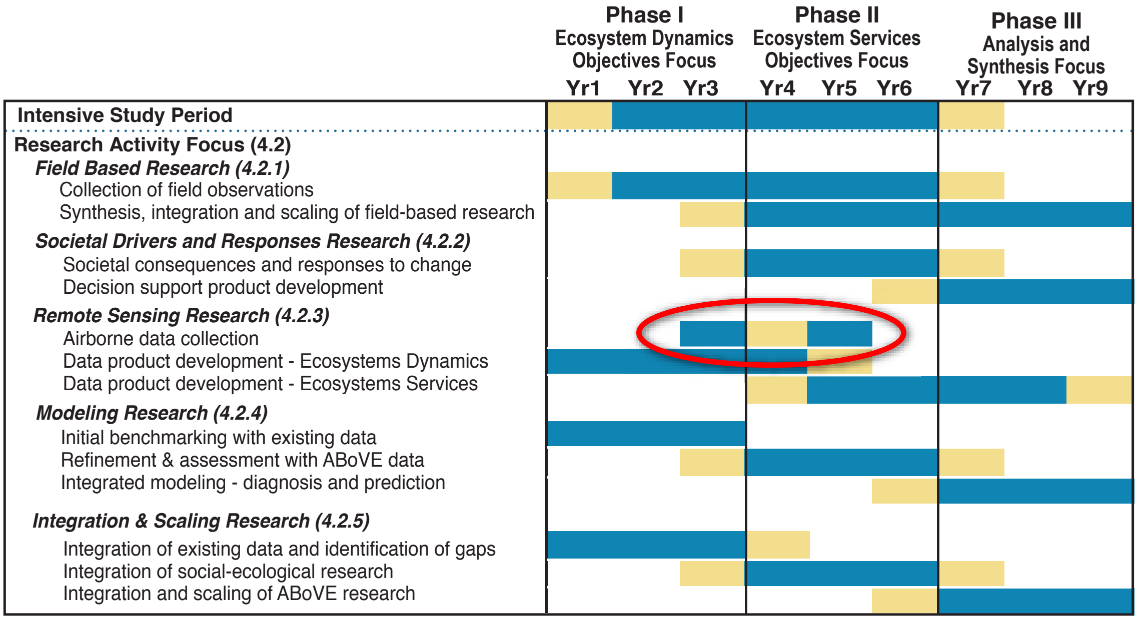


Figure 11. *Timeline for ABoVE Research Activities. Note the Airborne activities in years 3, 4, and 5, corresponding to 2017, 2018, and 2019.*

Some additional concept missions using aircraft are in various states of definition:

- *Arctic-COLORS (Arctic – Coastal Land Ocean Interactions)*
- *EXPORTS (EXport Processes in the Ocean from RemoTe Sensing)*
- *CAMPEx (Cloud-Aerosol-Monsoon-Philippines Experiment)*
- *Atmospheric chemistry in support of GEO-CAPE*
- *SnowEx campaign (like CLPX)*
- *Cloud studies (GPM-related)*

The most well-defined at this writing is Arctic-COLORS which is being designed to observe ocean color and correlated sea-life health at the mouths of major rivers in Alaska. A map of the study area is shown in Figure 12. The aircraft for this mission are still to be determined, but the science team has indicated that both manned and unmanned aircraft are anticipated.

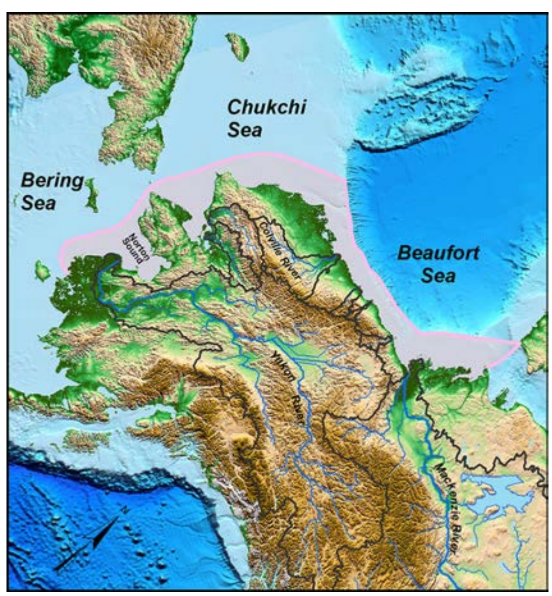


Figure 12. *Arctic-COLORS study area.*

Earth Venture - Suborbital

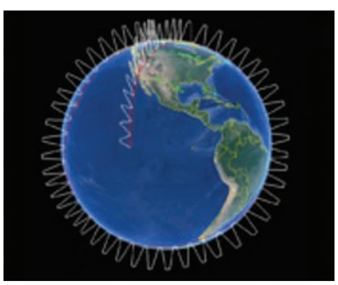
The Earth Venture Suborbital Missions have required, and will continue to require hundreds of flight hours on the ASP aircraft each year. EV-1 missions are concluding in 2015, as shown in Table 10.

Table 10. EV-1 flights, supporting aircraft, and status

Mission	Year	Aircraft
ATTREX / CAST	Concluded in 2015	Global Hawk
HS3	Concluded in 2014	Global Hawk
DISCOVER-AQ	Concluded in 2014	P-3, B-200, Falcon
CARVE	Concludes in 2015	Twin Otter, Sherpa
AirMOSS	Concludes in 2015	G-III

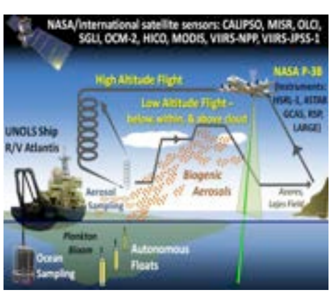
Earth Venture Suborbital – 2 (EVS-2)

Six new Earth Venture – Suborbital missions were awarded in 2015 with flight support required through 2019. The missions are described briefly below with a summary of aircraft requirements listed in Table 11. A preliminary schedule of aircraft-related activities is shown in Figure 13. The map in Figure 14 shows the broad reach of these missions.



Atmospheric Tomography Experiment (Atom) – Harvard University (Steve Wofsy)

This investigation will study the impact of human-produced air pollution on certain greenhouse gases. Airborne instruments will look at how atmospheric chemistry is transformed by air pollutants and at the impact of methane and ozone, which affect climate. Flights of NASA's DC-8 will originate in Palmdale, California, fly north to the western arctic, south to the South Pacific, east to the Atlantic, north to Greenland, and return to California across North America.

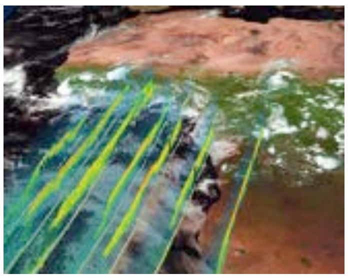


North Atlantic Aerosols and Marine Ecosystems Study (NAAMES) – Oregon State University (Mike Behrenfeld)

This investigation will improve predictions of how ocean ecosystems would change with ocean warming. The mission will study the annual like cycle of phytoplankton and the impact small airborne particles derived from marine organisms have on climate in the North Atlantic. The large annual phytoplankton bloom in this region may influence the Earth's energy budget. Research flights on NASA's C-130 aircraft will be coordinated with a (UNOLS) research vessel.

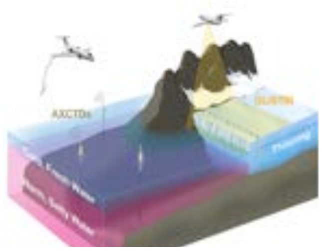
Atmospheric Carbon and Transport (ACT)-America – Penn State University (Kenneth Davis)

This investigation will quantify the sources of regional carbon dioxide, methane and other gases, and document how weather systems transport these gases in the atmosphere. The research goal is to improve identification and prediction of carbon dioxide and methane sources and sinks using spaceborne, airborne and ground-based data over the eastern United States. Research flights will use NASA's C-130 and UC-12 aircraft.



Observations of Aerosols Above CLouds and their InteractionS (ORACLES) – ARC (Jens Redemann)

Oracles will probe how smoke particles from massive burning in Africa influence cloud cover over the Atlantic. Particles from this seasonal burning that are lofted into the mid-troposphere and transported westward over the southeast Atlantic interact with permanent stratocumulus "climate radiators," which are critical to the regional and global climate system . NASA aircraft , including the P-3 and ER-2 will fly this mission out of Walvis Bay, Namibia.



Oceans Melting Greenland (OMG) – JPL (Josh Willis)

The objective of OMG is to investigate the role of warmer, saltier Atlantic sub-surface waters in Greenland glacier melting. The study will help pave the way for improved estimates of future sea level rise by observing changes in glacier melting where ice contacts seawater. Measurements of the ocean bottom, as well as seawater propertied around Greenland, will be taken from ships and the air using several aircraft including both NASA Gulfstream-III platforms.

COral Reef Airborne Laboratory (CORAL) – Bermuda Institute of Ocean Science, Inc. (Eric Hochberg)

This investigation will provide critical data and new models needed to analyze the status of coral reefs and to predict their future, especially under scenarios of predicted environmental change. CORAL will make high density observations for a large sample of reefs (~8% of global reef areas) that occur across a broad range of environmental conditions, implemented in 8 campaigns across 10 coral reef regions in the Indian, Pacific, and Atlantic Ocean. CORAL will fly PRISM, a new multispectral imager, on an NSF/NCAR G-V aircraft over a 3-year period.

Table 11. EVS-2 Aircraft Requirements

Mission	Location	Dates (see schedule)	Aircraft	Primary Requirements
Atom	Multiple – see map	2015 - 2018	DC-8	Altitude, range, payload capacity
NAAMES	North Atlantic / Azores	2015 - 2018	C-130	Range, payload capacity
ACT-America	Midwest – Eastern US	2015 - 2018	C-130, B-200	Altitude, payload capacity
ORACLES	Coast of Africa / Namibia	2016, 2017, 2018	P-3, ER-2	Range, payload capacity, altitude
OMG	Greenland	2015 - 2020	G-3, C-20 (G-III)	Combined range and payload capacity
CORAL	Indian and Pacific oceans, Caribbean	2015 - 2018	ER-2, GV	Altitude and endurance

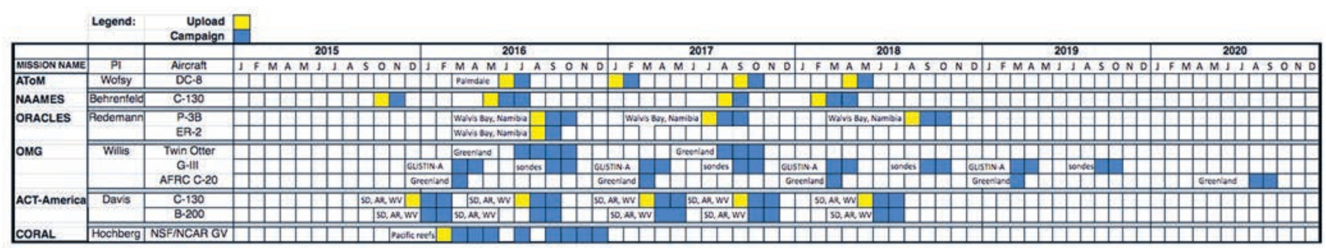


Figure 13. *Nominal schedule for EVS-2 missions.*

Notes:
ATоM = Atmospheric Tomography Experiment
NAAMES = North Atlantic Aerosols and Marine Ecosystems Study
ORACLES = Observations of Aerosols above Clouds
OMG = Oceans Melting Greenland
ACT-America = Atmospheric Carbon and Transport-America
CORAL = Coral Reef Airborne Laboratory

Figure 14.
Locations of EVS-2 Missions

Scheduling the aircraft for EVS-2 missions was a complicated exercise because of conflicting needs. Three of the awarded missions had requested the P-3; C-130s will be used as replacements in two cases to avoid schedule conflicts. CORAL will fly on the NSF/NCAR Gulfstream V, as it best suited to the payload and imaging needs of the mission.

Other requirement implications from the EVS-2 proposals suggest the following:

- *There is increased interest in polar regions (Arctic, Greenland, Alaska, Antarctic).*
- *A continued interest in weather includes especially a desire to study "atmospheric rivers" in the storm systems off the north-east Pacific Ocean.*
- *More than half of the mission concepts call for multiple aircraft, some in stacked formation (see Figure 15).*
- *A large fraction of mission concepts call for altitude profiles during flight.*

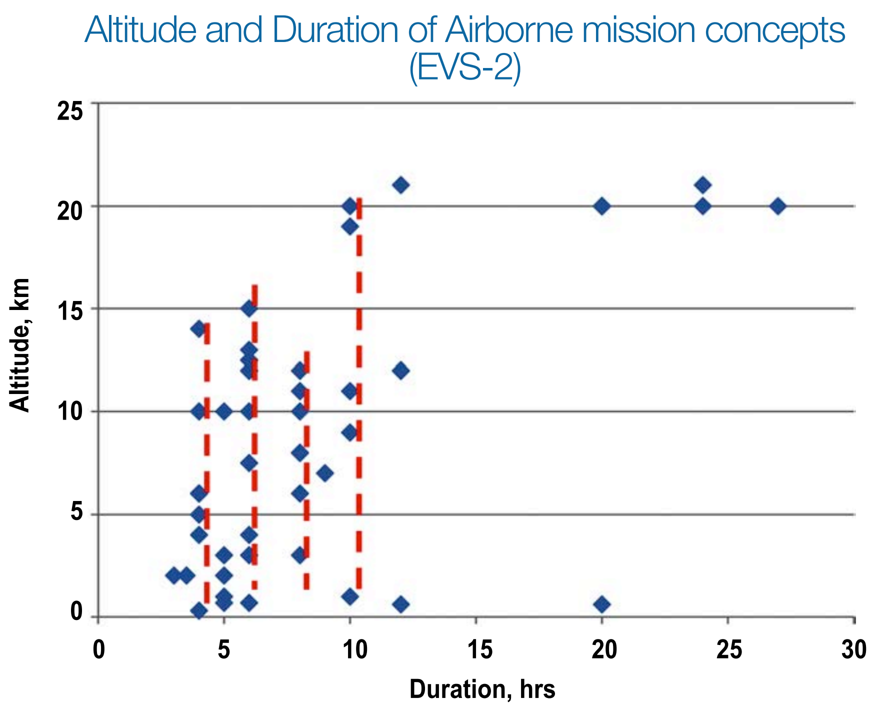


Figure 15. *Altitude and duration of airborne mission concepts for EVS-2. (Note the numerous suggested flight profiles.)*

Aircraft requirements related to NASA ESD instrument development

The Airborne Science Program supports technology development, particularly flight test of new instruments and observational techniques, many of which are ultimately destined for space. Instrument test flights can be scheduled by investigators with support or funding from a variety of sponsors or agencies. Many are sponsored by NASA's Earth Science Technology Office (ESTO) [http://esto.nasa.gov]. While ESTO solicits, awards, and manages the technology development projects, investigators work with platform operators to schedule their instruments for integration and test. Near-term flight test plans (as of 30 March 2015) are shown in Figure 16. Some will be ESTO-supported and others are proposed or expect to be supported from other programs.

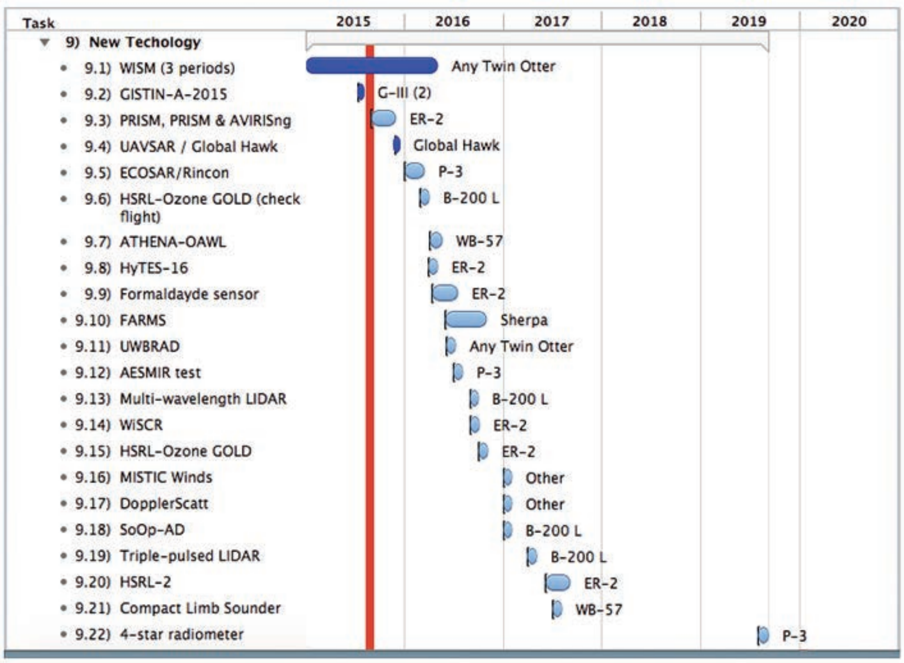


Figure 16. *Technology Development test plans.*

Aircraft requirements for instrument development projects are determined by the observational requirements of the instrument and are usually dictated by a given flight altitude (e.g. ER-2 or WB-57 for high altitude) or the need to have engineers/scientists on-board. When possible it is advantageous to fly multiple systems collocated on the same flight to provide complementary datasets and conduct intercomparisons, in addition to reducing costs. Two examples of this are the ASCENDS lidar instrument development flights on the DC-8 and the LVIS and UAVSAR flying together on the Global Hawk. Another possibility is a future opportunity to fly HyTES and AVIRIS-ng together on the G-III, if windows can be appropriately located on the G-III.

The solicitation schedule for both the Instrument Incubator Program (IIP) and the Airborne Instrument Technology Transition (AITT) program is shown below and it's anticipated that these will result in ongoing need for high altitude, medium lift as well as medium altitude medium to heavy lift aircraft activities.

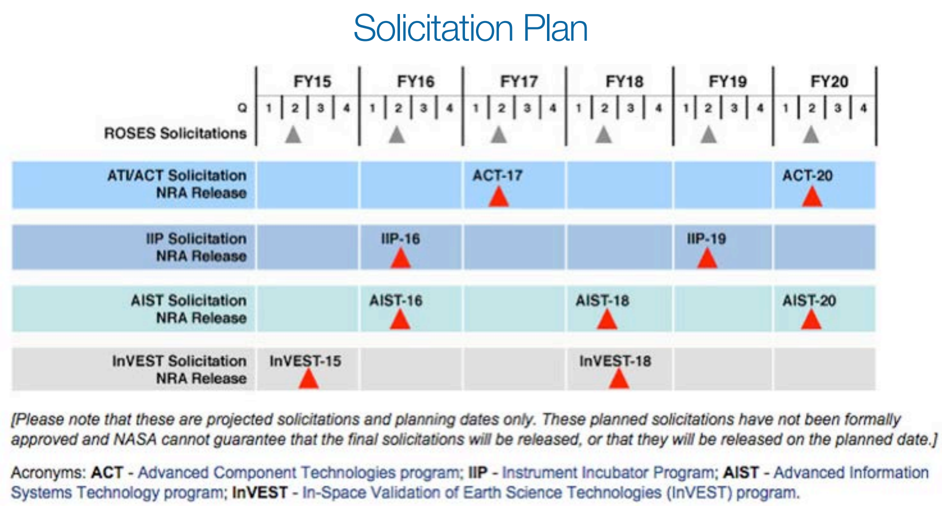


Figure 17. *NASA ESTO solicitation schedule.*

Looking Ahead: The Next Decadal Survey

The next NRC Decadal Survey for Earth Science is expected in early 2017. Plans are already underway for accepting input from the science community and forming working groups. The 2007 recommendations for satellite missions were ambitious and costs were underestimated. It is likely that some of the same observations and measurements will again be recommended, since many of the science needs are still pressing. An emphasis on climate should be expected, given that the "2010 NASA Response to Climate Plan"[2] identified new climate measurements, even beyond those in the 2007 decadal survey. Airborne Science support will still be needed, and possibly with more urgency to cover the time gaps till new missions can be launched. In addition, a new emphasis on continuity, as in the Sustained Land Imaging (SLI) initiative[3] could be included.

Recent input from the science communities

During late 2014 and early 2015, several Earth Science communities met to begin planning for the next Decadal Survey. These activities focused on the primary measurements and observations needed to address the most pressing questions in each science area. Presented in this section are summaries of airborne requirements either taken directly or inferred from the reports of those activities.

[2]***Responding to the Challenge of Climate and Environmental Change:*** *NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space. June 2010*

[3]*"Sustainable Land Imaging Architecture Study"; J. M. Nelson, D. T. Jenstrom, Pecora Conference, Denver 17-20 Nov. 2014*

Atmospheric Composition and Chemistry (based on 2014 workshop at ARC)

"The research community needs a combination of remote sensing and in situ (aircraft) observations integrating cloud dynamics, microphysics, and chemical properties."

Table 12. Suggested airborne activities for Atmospheric Composition and Chemistry in upcoming Decade

Mission	Description	Features
Tropospheric Chemistry	SEAC4RS – like, plus NH3	Multi-aircraft to measure convection, gases, aerosols and clouds
	SEAC4RS-like, plus LIDAR	Combined aircraft and satellite
	SEAC4RS-like	In tropics
Lightning contributions to tropospheric chemistry	Halogens and radicals in the troposphere	Simultaneous chemistry from aircraft and lightning measurements from ground
	Same	Simultaneous with satellite measurements
	Same	Night flights and measurements
Stratospheric Composition	In situ measurements including temperature	In the stratosphere = high altitude; multiple measurements = large payload capacity
	Strat-trop exchange	Profiles through the tropopause
	Synergistic campaign	Aircraft, ground and satellite

Notes on Stratospheric Composition (SC)

Meeting the SC science goals requires measurement of an array of coupled tracers, chemically reactive intermediates, and radicals. These observations can be obtained by a synergistic deployment of orbital, sub-orbital measurement platforms, and ground-based remote sensing observations.

To detect trends in climate-relevant stratospheric ozone, water, aerosols, and temperature, it is critical that observations of profiles of these species continue with at least current spatial and temporal resolutions.

Clouds

Table 13. Suggested airborne activities for Clouds, Aerosols and Atmospheric Radiation for upcoming Decade

Mission	Description	Features
Aerosol-Cloud-Precipitation Interaction	Vertical distributions	Multi-aircraft: 1 for in situ and 1 for remote sensing; includes LIDAR and Doppler Radar
	SNOW observations	Multi-aircraft, plus ground measurements
	SNOW cal/val	Satellite observations plus aircraft observations / measurements at high latitude and over oceans
Aerosols	Local and column optical depth	From top-of-the-atmosphere = high altitude
Atmospheric Radiation	IceBridge-like (systematic, routine flights)	Payload to include far-infrared instrumentation

- *Many of the cloud types associated with the cloud science questions are optically thick in the traditional visible and infrared observing bands. These clouds tend to be optically thin in the microwave and submillimeter wavelengths bands. Therefore, passive and active (including Doppler) measurements in the microwave and submillimeter wave lengths are fundamentally important.*

- *Optical lidar, including high spectral resolution (HSRL) technology, is critically important to characterizing the aerosol concentrations and composition and the properties of thin ice clouds.*

- ***In Situ measurements are fundamental. In particular, in situ aircraft flying in tandem with remote sensing aircraft is a powerful combination and highly synergistic.***

Atmospheric Dynamics

Table 14. Suggested airborne activities for Atmospheric Dynamics for upcoming Decade

Mission	Description	Features
Lightning	Lightning, its production of NOx, the effects on ozone, and connections to storm parameters	Aircraft carrying NO, NO2; Doppler and polarimetric radar, plus lightning monitor
Convection / Outflow	SEAC4RS-like, DC-3-like	Multiple aircraft; SEAC4RS payloads, plus Radar; at cloud tops
	SEAC4RS-like; diurnal	With full diurnal cycle
	SEAC4RS-likeP	lus ground-based Doppler radar
Stratiform region	Comparisons with convective regions	Multiple aircraft measuring simultaneously at various altitudes; mid-latitudes and tropics

Terrestrial Ecosystem, Carbon Cycle, Landcover/Landuse Change, Biodiversity (TECLUB) Decadal Planning

(based on 2014 meeting resulting in a 2015 white paper, and notes from April 2015 CCE joint science meeting)

TECLUB measurement needs identified for the next decade will require maintaining legacy capabilities in order to extend the multi-decade 30 m resolution data records well into the future; but also will require an increase in satellite overpass frequencies from ~bi-monthly to sub-weekly to ensure cloud-free data every week over the global land surface.

The traditional two-dimensional data records will need to be augmented with measurements of vegetation's vertical dimension, crucial to complete the picture of vegetation structure and its interaction with the environment.

Another dimension, simultaneous multi-angle, hyperspectral global observations, will also be needed to quantify photosynthetic rates and vegetation condition. Vegetation receives illumination from the entire upper hemisphere under a wide range of illumination angles. A near instantaneous, multi-angle multi-spectral view of vegetation will be essential to quantify highly variable photosynthesis rates.

The top priority for regional data that can be acquired suborbitally are accurate, dense atmospheric carbon concentration measurements over key regions, particularly the tropics and the arctic.

Comment: "Aircraft-based in situ GHG concentration and flux networks MUST be maintained."

Table 15. Suggested airborne activities for TECLUB for upcoming Decade

Mission	Description	Features
GHG / carbon concentration and flux	Regional atmospheric data: carbon concentrations	Manned aircraft or UAS in tropics, arctic, boreal / temperate forests
	Mid-latitude	Carbon fluxes from power plants
	"High density"measurements at the boundary later	"High density" = high resolution, frequent return; in situ and remote sensing
GHG / carbon concentration and flux	Terrestrial / ocean concentration	Amazonia, High latitudes, oceans
	Full vertical carbon cycle	Ground-air-satellite synergies
	Model improvements	Species measurements combined with climate and weather measurements
Vegetation	3-dimensional structure, especially vertical structure	Requires Lidar + inSAR + Radar
	Airborne data for cal/val of soil processes and hydrology	SMAP cal/val
	Multiple scales	Airborne combined with field data for multiple scales
	Vegetation function	Airborne imaging spectroscopy, especially as simulator for satellite measurements
	Missing data / under-sampled and vulnerable regions	-Land-ocean interface -Coastal wetlands -Tree line -Ecotones (An ecotone is a transition area between two biomes.)
Land cover Land use change	Urban areas; targeted under-sampled areas	Airborne Lidar, combined with high resolution optical satellite data
	Seasonal observations of vegetation in urban areas	Airborne Lidar, combined with high resolution optical satellite data
	Deforestation	Measure changes in albedo

Telemetry and Mission Tools Requirements

The Airborne Science Program is more than aircraft – today's missions require high speed onboard data networks, satellite communications, and internet-based software interfaces for mission scientists. It is important in planning and carrying out the science missions to make use of advanced flight planning and tracking tools, real-time data access and processing, and on-board navigation and inertial position monitoring. This requires real-time telemetry of data from both the aircraft and the science instruments. The telemetry and facility instruments available within the Airborne Science Program are described in Appendix A.

In addition, scientists on the ground need situational awareness with regard to weather conditions and other environmental factors in the vicinity of the aircraft in flight. The last few years have brought significant capability to the Airborne Science Program under the umbrella of the Mission Tools Suite. Current functions are listed in Table 16. Scientists have expressed interest in additional functionality, primarily in terms of path planning coordinated with related Earth Science satellites. Some requests are listed in Table 17.

Table 16. Functions of the Mission Tools Suite

Function
• Remotely monitor real-time aircraft location • View current and archived aircraft flight tracks • Add information overlays from a curated product registry • Customize user workspaces • Communication and collaboration tools • Integrated IRC (Internet relay chat) client supporting multiuser and person-to-person private chat • Remotely monitor real-time instrument engineering data • Plotting and graphing

Table 17. Additional capabilities requested by science community

Function
• Visualization of satellite swath during overpass • Mission playback capability • Need tools for estimating the time required for a given flight leg, together with overlays of satellite imagery or numerical model output. • A tool to plan payloads would be useful. Something that would estimate whether a user-defined payload can fit in a weight, volume and CG envelope of a given platform. • A method of storing, integrating, and processing data similar to the "Field Catalog" developed at NCAR would be very useful for complex NASA airborne missions • When we talk about multiple aircraft, we need more sophisticated, automated flight scheduling/planning software.

Other recommended improvements include:

- *Improve National Airspace (NAS) tracking for unequipped NASA and ASP mission participating aircraft. The current system for obtaining this data is not very robust and has relied on a decade-old ARMD system, which has a variety of stability and reliability issues. Furthermore, obtaining tracking information via the FAA ASDI feed is no longer approved by the FAA. Switching to the new FAA system (SWIM) is necessary to provide this capability, and to provide the Airborne Science Program with a more reliable feed.*

- *Improvements to the archived track data and access. The current system is limited to specific users and is difficult to use. Reporting and historical documentation requires greater and easier access to this data.*

- *Satellite Communications (SatCom) budget increases and additional hardware to improve mission situational awareness (i.e., RADAR, Cameras, ADS-B). It would be very useful for a variety of missions if operators on the ground could have access to camera data from platform aircraft. This requires an aircraft to have a camera, but once equipped, some budget to send images to the ground is needed. Typically this has been a "nice to have" for a mission, because constrained satcom budgets have meant prioritizing what can be sent to and received from the aircraft. However, real-time imagery can be a powerful situational awareness tool. It would be useful to make it a core capability for some aircraft, particularly where there is a sufficient ground support presence.*

- *This recommendation also applies to any other data that could be collected from the aircraft and sent to the ground for additional evaluation. Two such examples are RADAR and ADS-B data. For a variety of missions, especially those that are multi-aircraft campaigns, the data from one aircraft can be very useful for the planning and tasking of another aircraft.*

- *Therefore, the general recommendation is to increase SatCom budgets for data to improve mission situational awareness. This will, in turn, improve mission operations in a variety of circumstances.*

4. INPUT FROM CENTER REQUIREMENTS SURVEY AND ASP REQUIREMENTS MEETING

Process

During the fall of 2012, each of the NASA Science Centers was sent a survey to describe as quantitatively as possible, the science requirements for airborne science capabilities. The survey results were iterated several times to clarify some answers. In April 2013, an ASP web meeting was held to review the survey results and discuss the needs with the ASP program and NASA Earth Science program managers, including the Research and Analysis director.

The NASA Centers surveyed and prime respondents are listed in Table 18. Input was collected from multiple sources and scientists within each Center.

Table 18. NASA Centers surveyed and respondents

Center	Respondents
Ames	Steve Hipskind
Goddard	Paul Newman, Matt McGill, Lisa Callahan
JPL	Gary Lau, Mike Gunson, Bill Mateer
LaRC	Bruce Doddridge
MSFC	Michael Goodman

In the pages of requirements delivered, the areas addressed included:

- *Decadal Survey satellite missions*
- *Other satellite missions*
- *Science focus and process study areas*
- *Earth Venture*
- *Technology demonstration*
- *Applications*
- *General aircraft and program needs*

Respondents were asked to address the following questions:

1) What are the current capabilities within ASP that your community relies upon and will continue to rely upon for the foreseeable future?

2) What capabilities are lacking and in need of development (platforms, sensors, telemetry, data systems, mission management)? What is the time frame?

3) What are the added benefits of the new capabilities? What impact would there be if these new capabilities don't materialize?

4) What major missions/campaigns are planned over the next 5 years? 10 years?

5) Please describe 4-5 notional mission concepts that represent the breadth of science desired. What Earth Science program focus areas do these concepts represent?

6) How important is payload data telemetry during a mission?

7) What tools would be useful for planning airborne science missions?

8) What new sensors are planned or desired to service your science community? What existing instruments will be in operations over the next 5-10 years?

Where practical we wanted to understand capabilities required rather than specific aircraft, but particularly in the near term, aircraft-specific requirements are needed as well.

Additional questions were added later to address specific issues about extreme altitude and endurance. All teams provided answers to these additional questions.

Results

The matrix of survey results and Center presentations were made available to all participants. The summary briefing can be found on the Airborne Science Program website. Following are some highlights.

- *Keep DC-8. The laboratory capability is especially needed for atmospheric science missions.*
- *Keep ER-2. The high altitude capability is needed for both process studies above most of the atmosphere and instrument development for satellite missions. The WB-57 is also available for high altitude science flights. JSC operates three WB-57 aircraft which could be employed for airborne science.*
- *Keep GH – make it less expensive and easier to use. The very long endurance of the Global Hawk is needed for weather, diurnal investigations and long-range missions.*
- *Add longer endurance capability in the 35,000 – 40,000 ft regime (size like B-200, but less expensive than the DC-8.). The ideal capability is not currently included in the ASP fleet.*

Figure 18 shows flight regime results in altitude-endurance space from the answers to the surveys. Figure 19 indicates which current platforms are needed in the future. Some of the most frequently noted needs are listed in Table 9. (In Figure 19, the terminology "core-funded" refers to the Earth Science Directorate subsidy to these assets in the ASP fleet. The JSC G-III aircraft is only subsidized through FY 2014.)

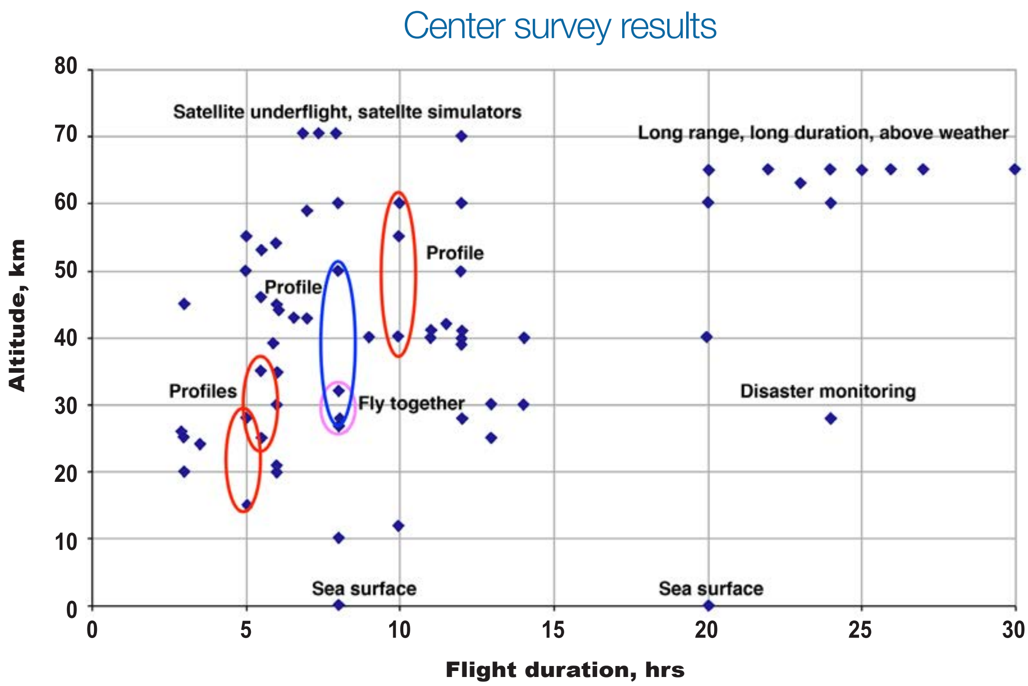


Figure 18. *Flight regime requirement space indicated in Center survey results.*

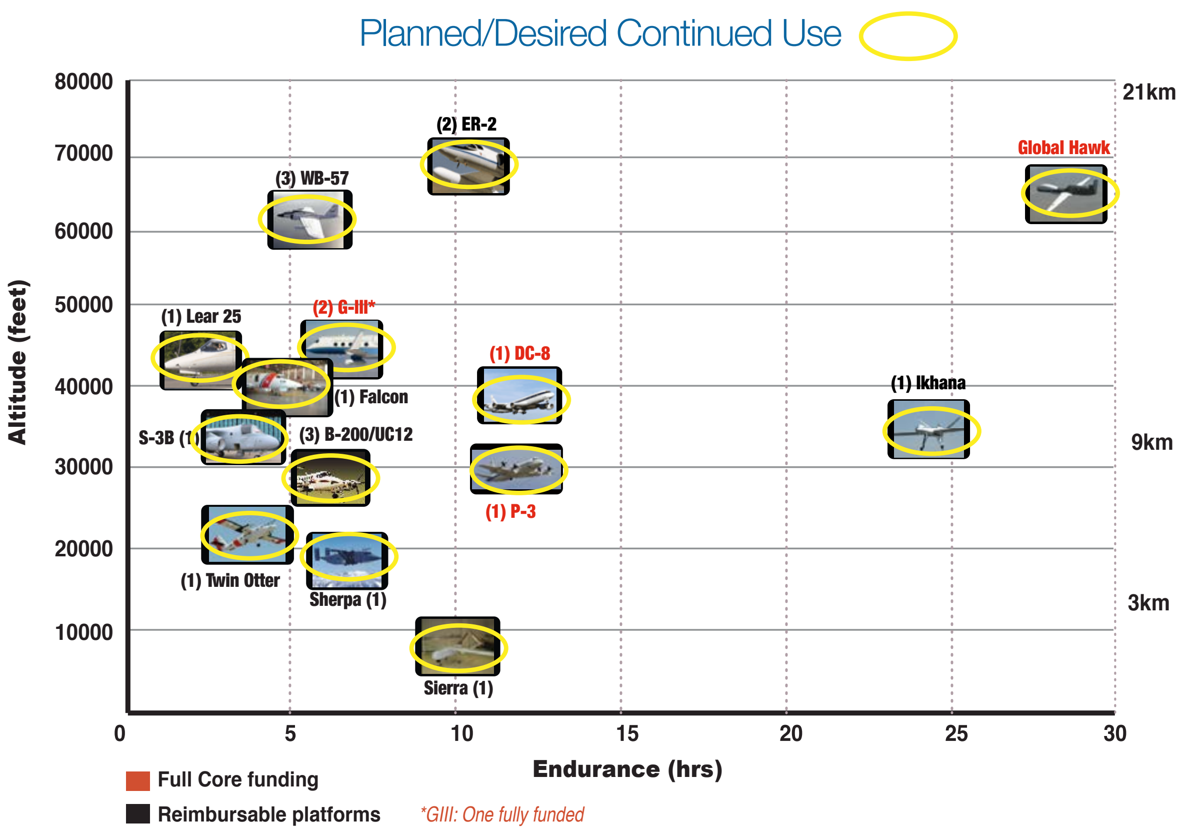


Figure 19. *Specific requirements for continued use of NASA aircraft indicated in Center survey results.*

Table 19. Comments noted during requirements analysis process

Platform needs	We need G-III – like capability on the East Coast. (To support terrestrial and ecosystem science without having long distance flights from California.) Note that the JSC G-III is based in Houston and can serve the East Coast.
	We currently have medium duration (4 hr) for small payloads. "We need longer duration (8 hr) without having to use a larger, more expensive platform."
	Heavy lift ABOVE 40 kft to reach tropopause (for trop/strat science) Note that WB-57 can meet this need.
	24+ hours at 65,000 ft with scientists on board
	Long-range capability to make measurements over the polar regions. (CO_2 measurements to support ASCENDS)
	Growing demand for low-altitude observation, especially for surface and ocean carbon fluxes, ice and snow measurements.
	Vertical profiles spanning the troposphere for studies of strat / trop species transport.
	Radiation Sciences Program and Atmospheric Dynamics Program would like an aircraft with ability to carry investigators and sensors into convective clouds in the icing region. Note that S-B3 aircraft could be used to meet this requirement, depending on altitude required.
Specific to UAS	– UAS access to more of the NAS, not just over oceans. – Ability (and permission) to fly 2 Global Hawks at one time. – High altitude long duration UAS to demonstrate space capability. – UAS (or other) with even longer observational periods – up to a week or more. – Increased use of small UAVs for science and application areas.
Instrument / platform needs	For lidar development, testing and inter-comparisons: aircraft with two large nadir ports, power for two lidar systems, large access doors, available GPS antenna, with flight hour cost below the DC-8.
	Ability to fly AVIRIS / AVIRIS-ng in conjunction with other instruments: HYTES, PRISM, UAVSAR (Could be done with G-III modifications.)
	Nadir ports on P-3 for radiometers
Mission tools	Increased bandwidth for downloading of near real time airborne instrument observations to scientists at field operations center or home institution
	Cost estimating tools

5. ANALYSIS, RECOMMENDATIONS AND CONCLUSIONS

This section provides analysis based on the previous sections. It also looks forward to the sources for future flight requests and how those might lead to future requirements. Recommendations and conclusions close this section.

The requirements activities leading up to this report support several broad conclusions:

- *The capabilities of Airborne Science Program are fairly well matched with the needs of the Earth science community.*
- *None of platforms supported by the Program appears to be superfluous, as frequent use of most aircraft is shown in the flight records.*
- *Several gaps in capability have been highlighted, especially at mid-altitude, ~8-hr duration.*
- *Some of the gaps have been filled by outside services, such as commercial vendors, the use of the NSF/NCAR GV, and by adding two C-130s to the fleet.*

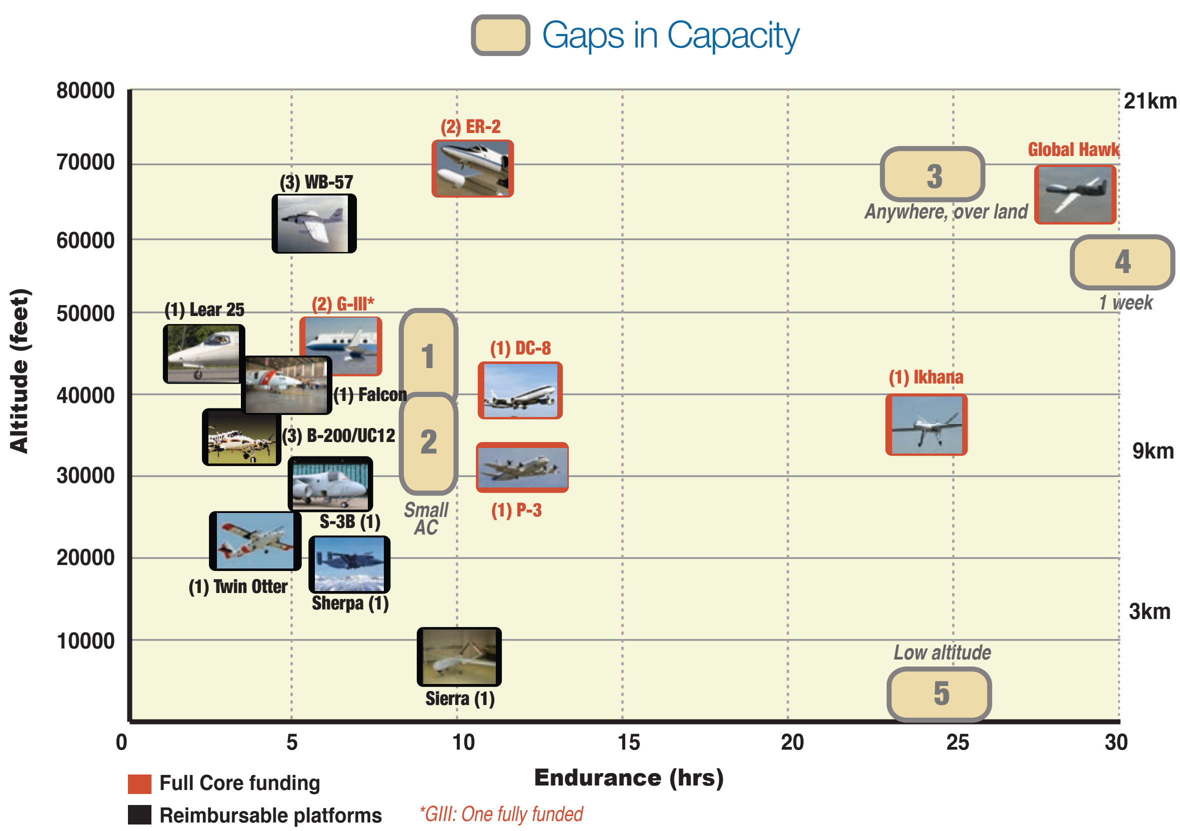


Figure 20. *Gaps in the existing fleet suggested by Center survey results.*

Figure 20 points out some gaps identified in the existing fleet as a result of the Center Survey and requirements activity. Table 20 explains the need behind each of these gaps. (In Figure 20, the terminology "core-funded" refers to the Earth Science Directorate subsidy to these assets in the ASP fleet. The JSC G-III aircraft was only subsidized through FY 2014.)

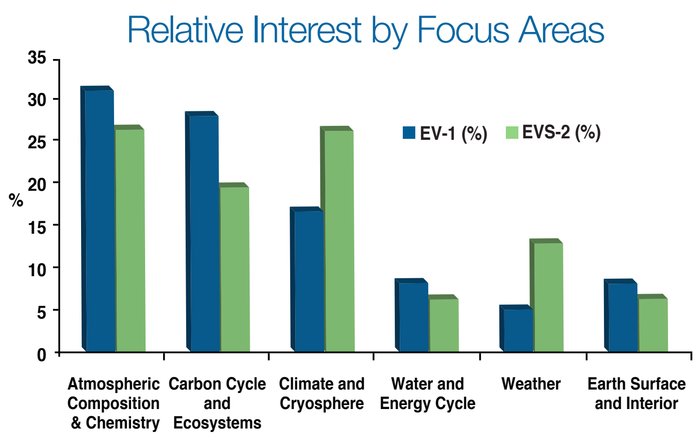
Table 20. Explanation of the gaps shown in Figure 21

Gap	Performance need	Science rationale	Possible solution
1. Flight altitude to 50kft, 8 hr duration, moderate payload	Similar to DC-8 flight regime, including nadir ports, but something smaller and less expensive	Lidar systems for weather and terrain mapping, but not full size laboratory.	Gulfstream V
2. Flight altitude 25 to 35 kft, 8 hr duration, small to moderate payloadpayload	Similar to King Air (B-200), but with longer duration	In situ sampling and ocean color both want 8 hrs, but flight characteristics and cost of B-200.	King Air B-350; possible business jet
3. Very high altitude (65+kft), long duration (24 hrs), fly anywhere	Similar flight regime as Global Hawk, ideally higher, not constrained to over ocean	Ability to see the evolution of atmospheric transport processes during a 24-hour period	Continue UAS in the NAS work; possible new aircraft
4. Very long endurance (~week)	Above weather and traffic with ability to follow event	Ability to monitor or track fire or pollutant plume, storm development	Aerial refueling, airship or balloon; new aircraft
5. Low altitude, long duration (or long range to target), where the target is remote or there are basing constraints	100 – 200 ft over water, stable flight; over land with auto pilot	Radiation science over the ocean; carbon flux measurement; coral or ocean color imaging	Long duration, low altitude UAS (OR ship launch)

Forecasting future requirements

The science questions that drive future Earth Science missions, in space, in the air, on the Earth Surface and below are articulated in the Earth Science plan and NASA Climate Change Plan. Airborne Science capabilities are driven by the need for measurements and observations both near and far, and from all regions of Earth. Sometimes it is difficult to see specific needs very far ahead. Programmatically, the next 5 years will see flight requests based on Earth Science satellite missions, field studies, technology development, many of them based on various NASA solicitations. The solicitations come out of science focus area programs, ESTO, satellite and ISS mission science teams and the Earth Science Pathfinder Program (ESSP), which manages Earth Venture. On the other hand, it is not difficult to imagine what the needs could be, given that the science questions are fairly well articulated, even if they evolve over time.

One place to look for requirements is to project the recent past into the near future. Proposals for EV-1 and EVS-2, for example, showed various interests, as shown in Figure 21.



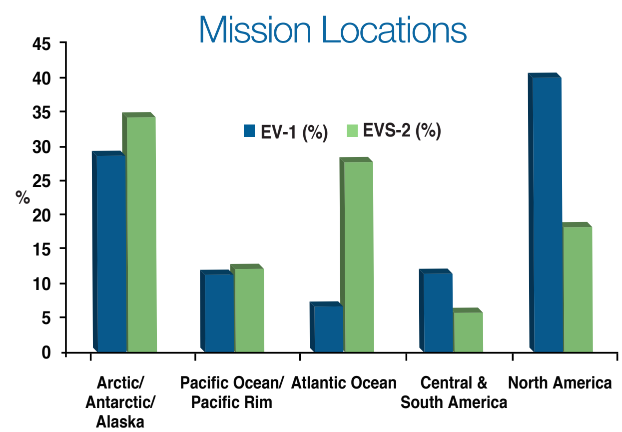


Figure 21. *Areas of interest for Earth Venture Suborbital missions.*

Some lessons learned from Earth Venture Suborbital that apply to future ASP requirements:

- *Needed another UAVSAR and a/c to carry it*
- *Needed another, more suitable a/c for PALS*
- *P-3 proposed for numerous studies; C-130 being readied for some leverage*
- *Airspace coordination skills are important, for both manned aircraft and UAS*
- *Science personnel can be limited, as well as a/c, payload, comm., etc personnel*
- *It is challenging to share payloads with other projects when they are involved in EV missions*
- *Accessing polar regions is a particular challenge, but important and ever more in demand*
- *Foreign basing is also a challenge that requires early planning*

Specific to UAS, it is also possible to predict some demand for UAS based on the proposals submitted to the UAS-enabled Earth Science call. The science and vehicles proposed for the 2010 A.40 call are shown in Figure 22. Based on the ongoing activities of UAS selected projects, several lessons for the future include:

- *There is a need for long-range UAS capabilities, long endurance, both low and high altitude*
- *There is a requirement for more reliable, higher bandwidth communications in the Arctic*
- *Common data systems for small to medium class UAS would facilitate the portability of payloads and reduce costs and engineering*
- *More diligence is required during the proposal development and review process, to validate the performance of COTS payloads for UAS.*

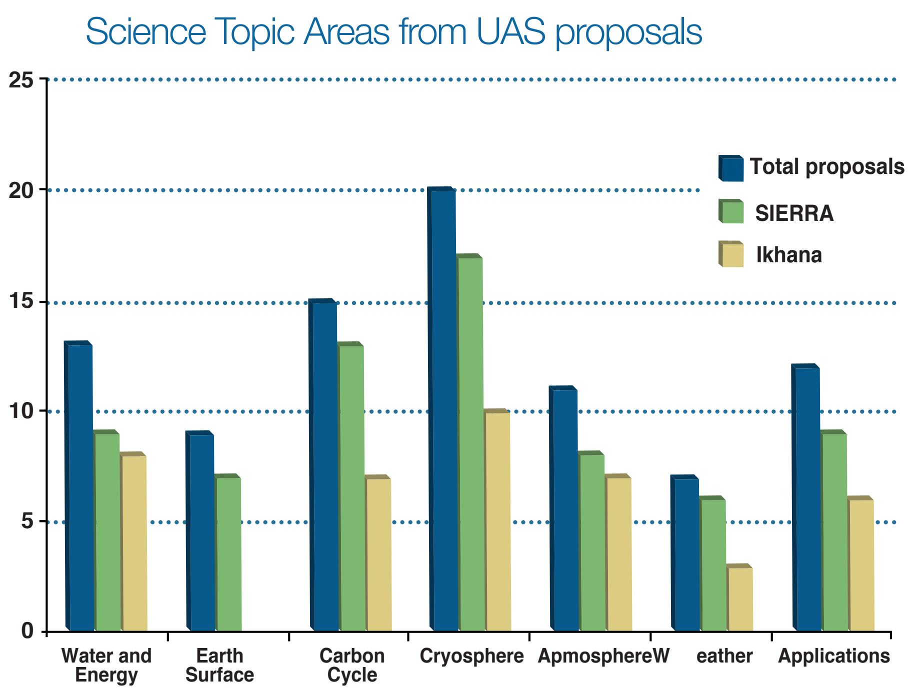


Figure 22. *Vehicles and Science proposed for UAS-Enabled Earth Science. (Note that each proposal required two or more UAS.)*

Planned R&A Solicitations with airborne component

Based on known and planned solicitations and activities, the Airborne Science Program can look ahead and prepare for flight requests, as suggested in Table 21.

Table 21. Flight requests anticipated based on the following activities

Solicitation	Proposals due and/or awards expected
ABoVE aircraft / platforms	2016
ESTO IIP 2016	2016
HyspIRI - tropics	2016
SnowEx	2016
ESTO AITT	2017
CampEX	2018

Cal/val plans for upcoming satellite missions ICESat-2 and SWOT are also forthcoming. Finally, the NASA Climate Response Plan calls for an emphasis on continuity of climate-related measurements and ASP capabilities may be required to fill gaps while awaiting satellite launch for some upcoming missions. An example is the NISAR mission, which will demand even more use of the UAVSAR system on the G-III.

Conclusions and Recommendations

Requirements for Airborne Science Program capabilities are found not only in the official Flight Requests (SOFRS), but also through upcoming mission planning activities, technology development, and discussions with NASA Earth Science program managers and the scientific community. Based on the information collected for this report, more than 50% of science flight hour needs are met using ASP-supported aircraft and more than 85% using NASA-affiliated aircraft. In recent years, the number of flight hours has continued to increase largely in support of Operation IceBridge and the Earth Venture projects, but it is expected that this trend will level once OIB is over.

While specific requirements are difficult to project far into the future because of the nature of the NASA solicitation and award process, it is clear that ASP capabilities will be needed in both the near (1-3 years) and mid-term (3-5 years) for satellite and ISS support (pgs 15-19), process studies (pg 20), instrument testing (pg 28) and Earth Venture (pg 26). The full spectrum of fleet capabilities is required, especially at the far edges of the altitude, endurance and payload-carrying envelopes. New capabilities are also required, especially for 8-hr duration flight over the entire altitude profile from 25,000 to 50,000 feet, but with perhaps smaller and less expensive systems.

The primary findings of this requirements survey are:

- *There are clear requirements for all aircraft currently in the core fleet given currently funded instrument development, satellite missions, R&A research, and the Earth Venture line of missions.*
- *All satellite missions currently in formulation have plans to use aircraft during one or more phases of their development and operations.*
- *Requirements for medium altitude- medium payload, business-class jet or Super King Air aircraft have increased and represent a gap in the current fleet, forcing projects to rely on less capable aircraft, or other agency aircraft.*
- *There are no platforms capable of providing low altitude long endurance measurements required for ocean and land surface fluxes and radiation measurements*
- *There is a continued call from the science community for high altitude long endurance platforms for providing geostationary-like measurements in addition to providing diurnal measurements of atmospheric phenomenon*

The mission tools and communications and data management capabilities which have been developed in the past few years are being utilized with ever greater frequency and utility, so much so that there is now demand for even greater functionality and speed. Specific recommendations for improvements in situational awareness include increased SatCom budgets and related hardware.

Suggestions and requests for new or improved capabilities are included in this report and follow-up between the ASP Director and science leads on specific requirements is recommended. Beyond investment targets for hardware and software, are several suggestions for improved program processes. These include:

- *Requesting an airborne planning element in all satellite mission programs, as early as KDP-A.*
- *A cost calculator for the various aircraft and support instrumentation, including integration estimates, for scientists to use in proposal planning.*
- *Routine updates to Flight Requests in SOFRS when flight dates change.*

APPENDIX A. ASSETS AND CAPABILITIES OF THE AIRBORNE SCIENCE PROGRAM

This Appendix contains a detailed description of the ASP program capabilities. More information can be found on the ASP website at http://airbornescience.nasa.gov.

Table A1. Current NASA Aircraft Platforms

Airborne Science Program Resources	Platform Name	Center	Duration (Hours)	Useful Payload (lbs)	GTOW (lbs)	Max Altitude (ft)	Airspeed (knots)	Range (Nmi)	Internet and Document References
ASP Supported Aircraft*	DC-8	NASA-AFRC	12	30,000	340,000	41,000	450	5,400	http://airbornescience.nasa.gov/aircraft/DC-8
	ER-2 (2)	NASA-AFRC	12	2,550	40,000	>70,000	410	>5,000	http://airbornescience.nasa.gov-/aircraft/ER-2
	Gulfstream III (G-III)(C-20A)	NASA-AFRC	7	2,610	69,700	45,000	460	3,400	http://airbornescience.nasa.gov-/aircraft/G-III_C-20A_-_Dryden
	Global Hawk	NASA-AFRC	26	1,500	26,750	65,000	335	9,000	http://airbornescience.nasa.gov-/aircraft/Global_Hawk
	P-3	NASA-WFF	14	14,700	135,000	32,000	400	3,800	http://airbornescience.nasa.gov-/aircraft/P-3_Orion
Other NASA Aircraft	B-200 (UC-12B)	NASA-LARC	5	2,000	13,500	28,000	220	1,000	http://airbornescience.nasa.gov-/aircraft/B-200_UC-12B_-_LARC
	B-200	NASA-AFRC	5	1,700	13,420	28,000	270	1,400	http://airbornescience.nasa.gov-/aircraft/B-200_-_DFRC
	B-200	NASA-LARC	5	2,000	13,500	28,000	220	1,000	http://airbornescience.nasa.gov-/aircraft/B-200_-_LARC
	B-200 King Air	NASA-WFF	6.0	1,800	12,500	28,000	275	1,800	https://airbornescience.nasa.gov-/aircraft/B-200_King_Air_-_WFF
	C-130 (2)	NASA-WFF	12	36,500	155,000	33,000	290	3,000	https://airbornescience.nasa.gov-/aircraft/C-130_Hercules
	C-23 Sherpa	NASA-WFF	6	7,000	27,100	20,000	190	1,000	http://airbornescience.nasa.gov-/aircraft/C-23_Sherpa
	Cessna 206H	NASA-LARC	5	646	3,600	10,000	150	700	http://airbornescience.nasa.gov-/aircraft/Cessna_206H
	Cirrus SR22	NASA-LARC	6.1	932	3,400	10,000	175	970	http://airbornescience.nasa.gov-/aircraft/Cirrus_Design_SR22
	Dragon Eye	NASA-ARC	<1	1	6	1000	34	3	http://airbornescience.nasa.gov-/aircraft/B-200_-_LARC
	Gulfstream III (G-III)	NASA-JSC	7	2,610	69,700	45,000	460	3,400	http://airbornescience.nasa.gov-/aircraft/G-III_-_JSC
	HU-25C Falcon	NASA-LARC	4.5	2,000	32,000	36,000	350	1,600	http://airbornescience.nasa.gov-/aircraft/HU-25C_Falcon
	Ikhana	NASA-AFRC	20	2,000	10,500	45,000	171	3,000	http://airbornescience.nasa.gov-/aircraft/Ikhana
	Learjet 25	NASA-GRC	2	2,000	15,000	45,000	350	1,000	http://airbornescience.nasa.gov-/aircraft/Learjet_25
	Learjet 35	NASA-GRC	4	4,200	19,600	45,000	350	2,300	
	S-3B Viking	NASA-GRC	6	12,000	52,500	40,000	350	2,300	http://airbornescience.nasa.gov/aircraft/S-3B
	SIERRA	NASA-ARC	10	100	400	12,000	60	600	http://airbornescience.nasa.gov-/platforms/aircraft/sierra.html
	T-34C	NASA-GRC	3	100	4,400	25,000	150	500	http://airbornescience.nasa.gov-/aircraft/T-34C
	Twin Otter	NASA-GRC	3	3,000	11,000	25,000	140	450	http://airbornescience.nasa.gov-/aircraft/Twin_Otter_-_GRC
	UH-1	NASA-WFF	2	3,880	9,040	12,000	108	275	https://airbornescience.nasa.gov-/aircraft/UH-1_Huey
	Viking-400 (4)	NASA-ARC	11	100	520	15,000	60	600	https://airbornescience.nasa.gov-/aircraft/Viking-400
	WB-57 (3)	NASA-JSC	6.5	8,800	72,000	60,000+	410	2,500	http://airbornescience.nasa.gov-/aircraft/WB-57

Figure A1 shows the range of aircraft capabilities in altitude – endurance space. Not all of these platforms are subsidized by the Earth Science Division. See Table A1 for the lists of those aircraft that are and are not ASP-supported. Figures A2 shows the same aircraft in altitude – range space. Figure A3 shows graphically the payload capability of the NASA Earth Science aircraft. Figure A4 shows all aircraft in the combined Interagency Coordinating Committee for Airborne Geoscience Research and Applications (ICCAGRA) fleet available for Earth Science.

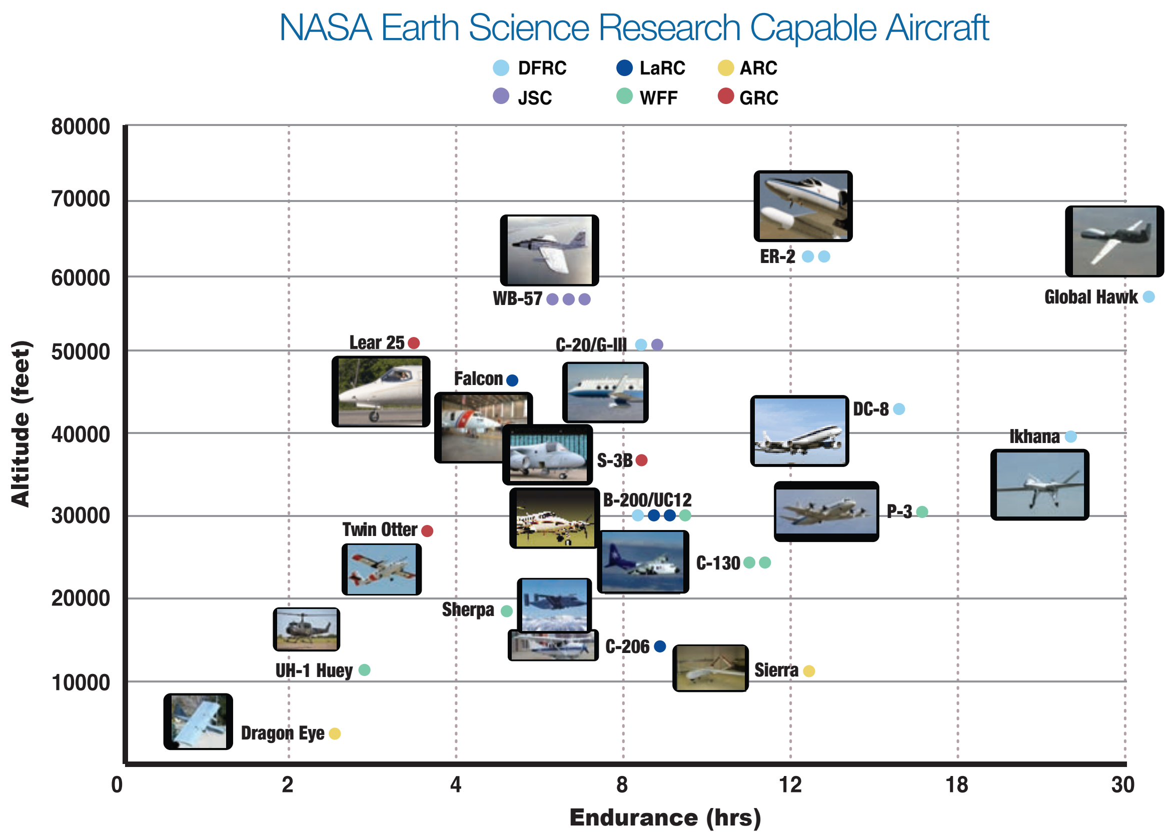


Figure A1. *ASP platform capabilities in altitude and duration - all available aircraft.*

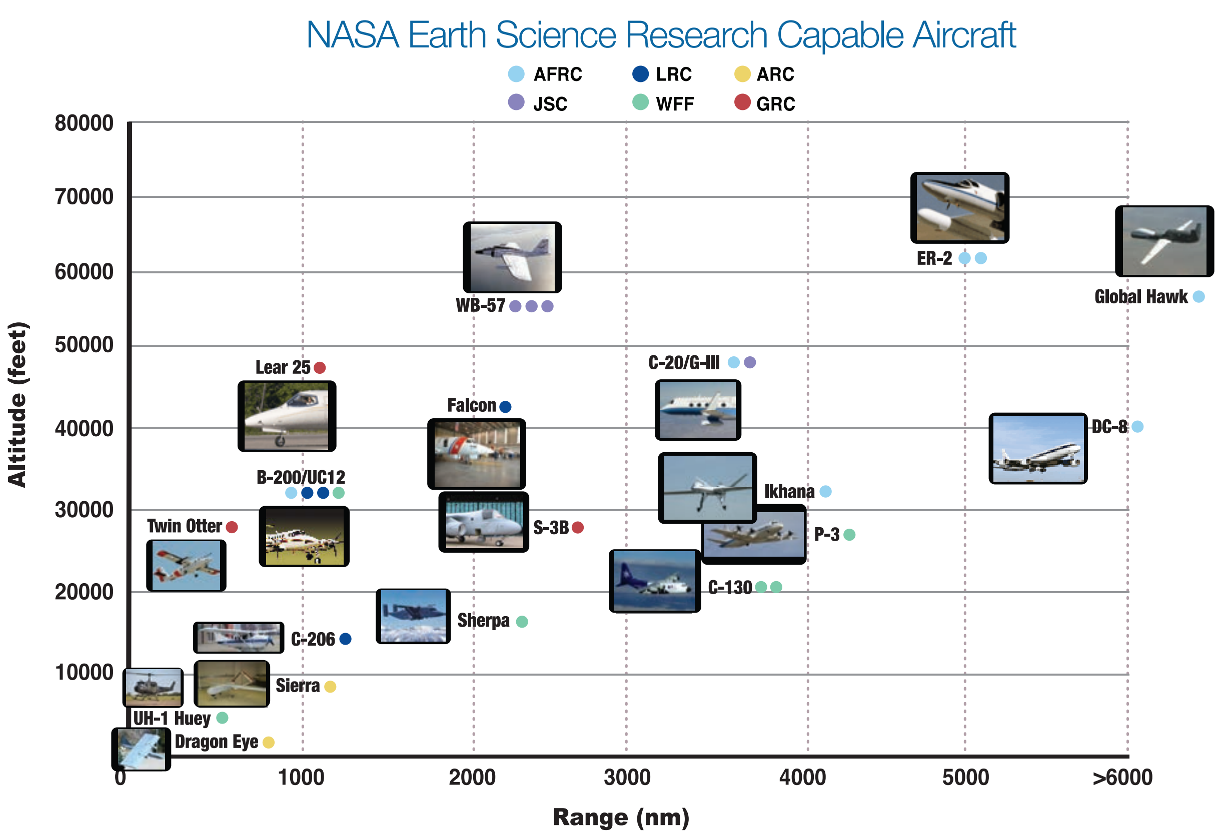


Figure A2. *ASP platform capabilities in altitude and range - all available NASA aircraft.*

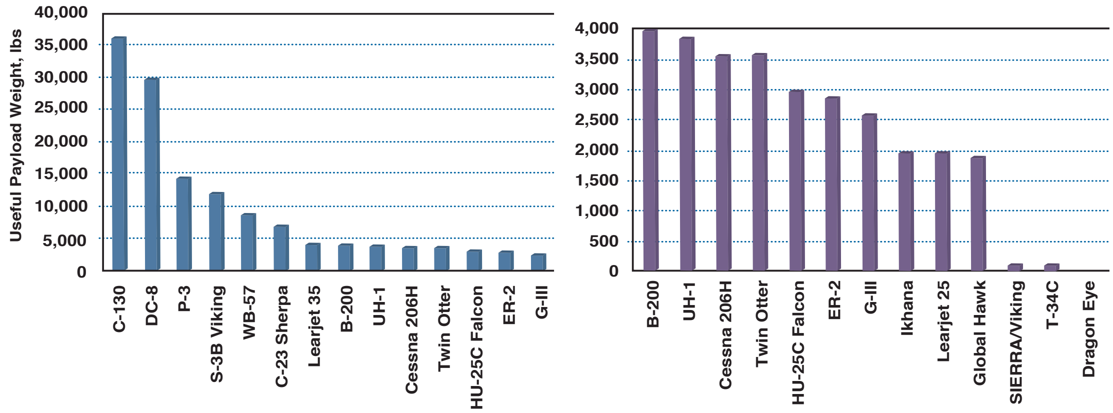


Figure A3. *Payload capability of NASA Earth Science aircraft.*

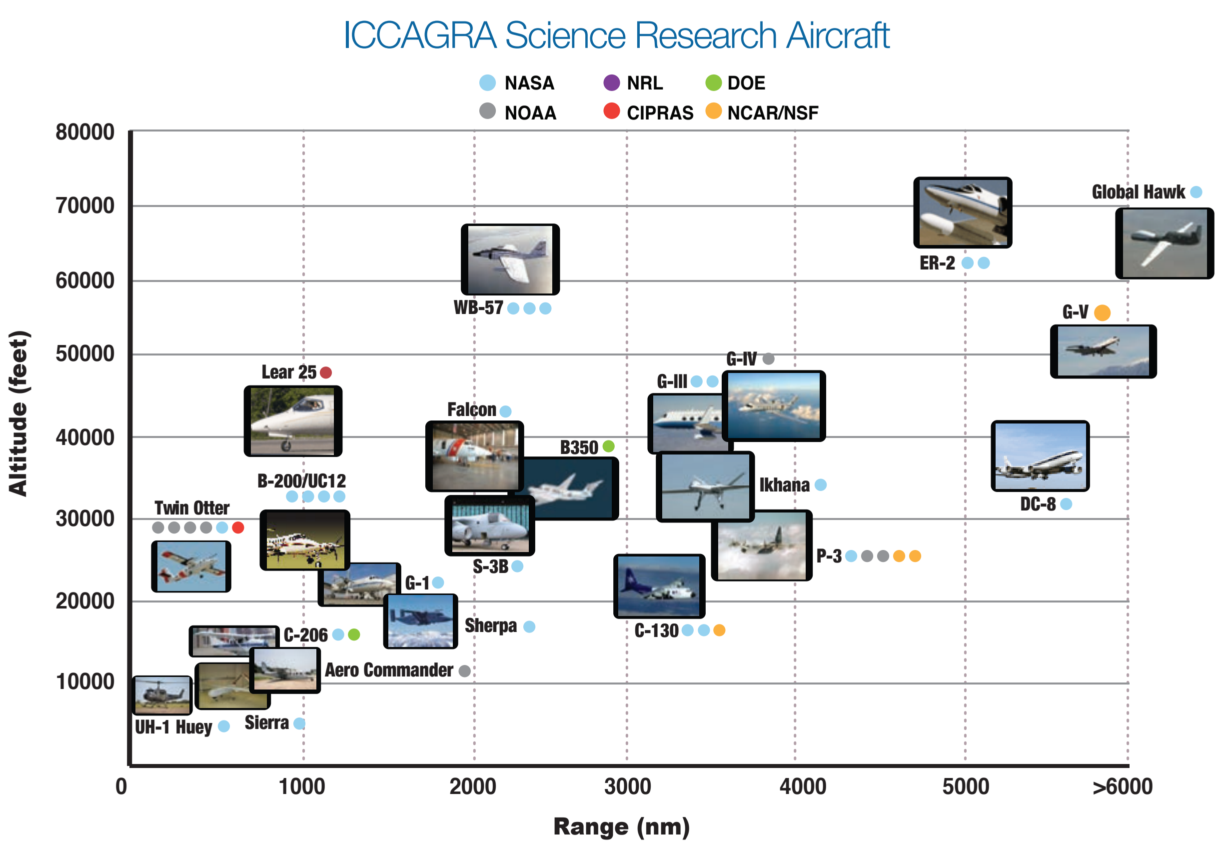


Figure A4. *All ICCAGRA aircraft are also available for Earth Science research.*

Table A2. Facility Equipment and Communications capabilities

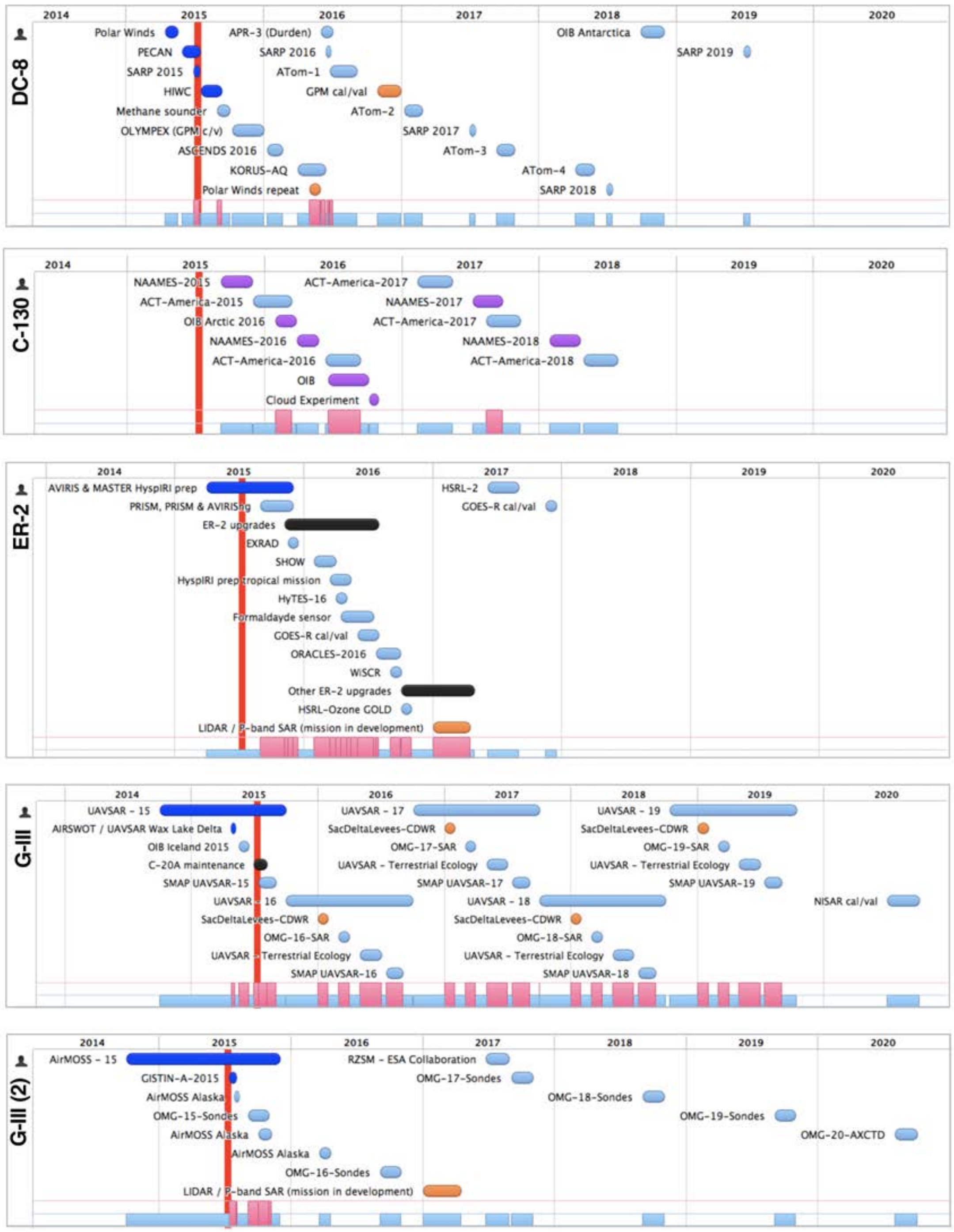
Airborne Science Program Facility Equipment		
Instruments/Description	**Supported Platforms**	**Support group / location**
DCS (Digital Camera System) 16 MP color infrared cameras	DC-8, ER-2, Twin Otter, WB-57, B200	Airborne Sensor Facility / ARC
DMS (Digital Mapping System) 21 MP natural color cameras	DC-8, P-3	Airborne Sensor Facility / ARC
POS AV 510 (3) Applanix Position and Orientation Systems DGPS w/ precision IMU	DC-8, ER-2, P-3, B200	Airborne Sensor Facility / ARC
POS AV 610 (2) Applanix Position and Orientation Systems DGPS w/ precision IMU	DC-8, P-3	2 at Airborne Sensor Facility / ARC 2 at WFF
DyNAMITE (Day/Night Airborne Motion Imagery for Terrestrial Environments) Full Color High Definition and Mid-Wave IR High Resolution Full Motion Video System	WB-57	JSC
Hygrometers	DC-8, P-3, C-130	Airborne Sensor Facility / ARC
IR surface temperature instruments	DC-8, P-3, C-130	Airborne Sensor Facility / ARC
High-speed 3D winds and aircraft attitude instruments	DC-8, P-3, C-130	Airborne Sensor Facility / ARC
Static air temperature instruments	DC-8, P-3, C-130	Airborne Sensor Facility / ARC
HDVIS High Def Time-lapse Video System	Global Hawk UAS	Airborne Sensor Facility / ARC
LowLight VIS Low Light Time-lapse Video System	Global Hawk UAS	Airborne Sensor Facility / ARC
EOS and R&A Program Facility Instruments		
Instruments/DescriptionS	**upported PlatformsS**	**upport group / location**
MASTER (MODIS/ASTER Airborne Simulator) 50 ch multispectral line scanner V/SWIR-MW/LWIR	B200, DC-8, ER-2, P-3, WB-57	Airborne Sensor Facility / ARC
Enhanced MAS (MODIS Airborne Simulator) 38 ch multispectral scanner + VSWIR imaging spectrometer	ER-2	Airborne Sensor Facility / ARC
AVIRIS-ng Imaging Spectrometer (380 - 2510nm range, Dl 5nm)	Twin Otter	JPL / JPL
AVIRIS Classic Imaging Spectrometer (400 – 2500nm range, Dl 10nm)	ER-2, Twin Otter	JPL / JPL
UAV_SAR Polarimetric L-band synthetic aperture radar, capable of Differential interferometry	ER-2, Twin Otter	JPL / JPL
NAST-I Infrared imaging interferometer (3.5 – 16mm range)	ER-2	U Wisconsin / LaRC
Satellite Communications systems on ASP aircraft		
Satellite Communications systems on ASPaircraft	**Supported PlatformsS**	**upport group / location**
Ku-Band (single channel) / > 1 Mb/sec	Global Hawk & Ikhana UAS; WB-57	NSERC / DFRC / JSC
Inmarsat BGAN (two channel systems) / 432 Kb/sec per channel	DC-8, WB-57, P-3,S-3B, DFRC B200, ER-2, Global Hawk	Airborne Sensor Facility / DFRC
Iridium (1 – 4 channel systems) / 2.8 Kb/sec per channel	Global Hawk, DC-8, P-3, ER-2, WB-57, G-III, SIERRA, C-130, others	Airborne Sensor Facility, NSERC /ARC

Table A3. Functions of the Mission Tool Suite

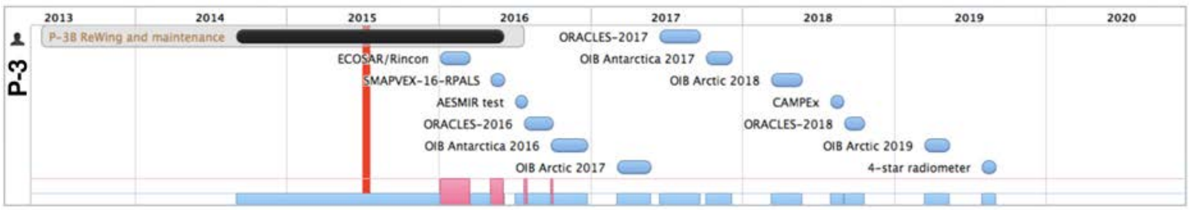
MTS Functions
• Remotely monitor real-time aircraft location • View current and archived aircraft flight tracks • Add information overlays from a curated product registry • Customize user workspaces • Communication and collaboration tools • Integrated IRC (Internet relay chat) client supporting multiuser and person-to-person private chat • Remotely monitor real-time instrument engineering data • Plotting and graphing

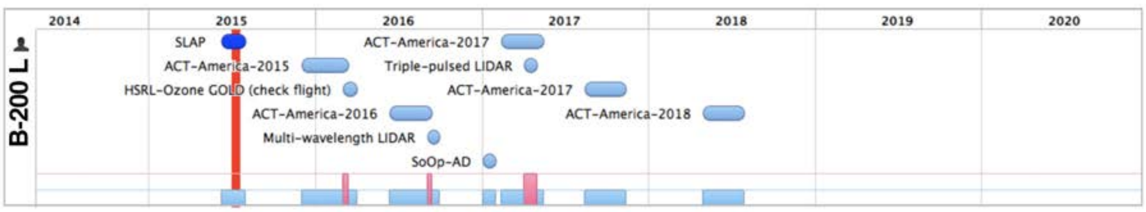
APPENDIX B. ASP 5 YEAR PLAN (as of mid 2015)

Airborne Science 5 Year Plan - by aircraft



Airborne Science 5 year plan by aircraft (continued)





Airborne Science 5 Year Plan by science area (as of mid 2015)

Task	Flt Hours	PS/PE/PM	Related Satellite/Sensor	2014	2015	2016	2017	2018	2019	2020
1) Atmospheric Composition and Chemistry										
• 1.1) AJAX (Iraci)	60	Jucks	OCO-2, ASCENDS		Alpha Jet					
• 1.2) Methane sounder	15	Chief technologist			DC-8					
• 1.3) EXRAD	100	Maring	ACE		ER-2					
• 1.4) ASCENDS 2016	30	Jucks	OCO-2, ASCENDS			DC-8				
• 1.5) SHOW	20	Jucks				ER-2				
• 1.6) CARAFE	10	GSFC	OCO-2			Sherpa				
• 1.7) KORUS-AQ	120	Pszenny	Geo-Cape, A-Train, SNPP, TEMPO			DC-8				
• 1.8) Chemistry Mission-in-development	30	Jucks	GEo-Cape			WB-57				
• 1.9) CAMPEx	120	Maring	A-Train, ACE					P-3		

Task	Flt Hours	PS/PE/PM	Related Satellite/Sensor	2014	2015	2016	2017	2018	2019	2020
2) Carbon Cycle & Ecosystems Science										
• 2.1) AVIRIS & MASTER HyspIRI prep	100	Turner/Neeck	HyspIRI		ER-2					
• 2.2) AVIRIS-ng (various)	146	Turner	HyspIRI		Any Twin Otter					
• 2.3) Carbon Monitoring System		CCE			Any Twin Otter					
• 2.4) HyspIRI prep tropical mission		Turner	HyspIRI			ER-2				
• 2.5) UAVSAR - Terrestrial Ecology	20	CCE	NISAR			G-III				
• 2.6) EXPORT (placeholder)		Bontempi				TBD				
• 2.7) LIDAR / P-band SAR (mission in development)		CCE					ER-2; G-III (2)			
• 2.8) CCE Field Campaign ABoVE	100	Kasischke					TBD			
• 2.9) UAVSAR - Terrestrial Ecology	20	CCE	NISAR				G-III			
• 2.10) South Asia LCLUC (placeholder)		Gutman	Landsat					TBD		
• 2.11) UAVSAR - Terrestrial Ecology	20	CCE	NISAR					G-III		
• 2.12) Arctic COLORS (placeholder)		Bontempi						TBD		
• 2.13) UAVSAR - Terrestrial Ecology	20	CCE	NISAR						G-III	
• 2.14) NISAR cal/val		CCE	NISAR							G-III

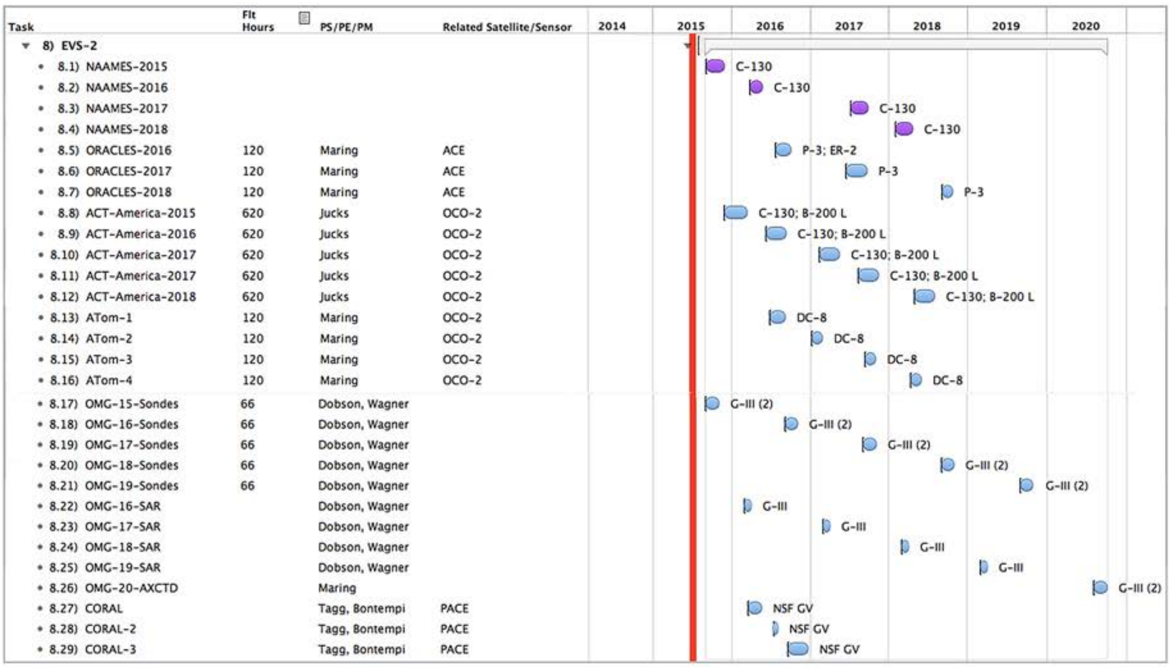
Task	Flt Hours	PS/PE/PM	Related Satellite/Sensor	2014	2015	2016	2017	2018	2019	2020
3) Cryospheric Science										
• 3.1) OIB Iceland 2015	60	Wagner	ICESat 2		G-III					
• 3.2) MABEL 2015(?)			ICESat 2		UC-12					
• 3.3) OIB Arctic 2016	300	Wagner; Tagg	ICESAT 2			C-130				
• 3.4) OIB Alaska 2016		Wagner	ICESat 2			Single Otter				
• 3.5) OIB	250	Wagner; Tagg	ICESat 2			C-130				
• 3.6) OIB Antarctica 2016	250	Wagner; Tagg	ICESat 2			P-3				
• 3.7) OIB Arctic 2017	300	Wagner, Tagg	ICESat 2				P-3			
• 3.8) OIB Antarctica 2017	250	Wagner, Tagg	ICESat 2				P-3			
• 3.9) OIB Arctic 2018	300	Wagner, Tagg	ICESat 2					P-3		
• 3.10) OIB Antarctica	250	Wagner, Tagg	ICESat 2					DC-8		
• 3.11) OIB Arctic 2019	250	Wagner, Tagg	ICESat 2						P-3	

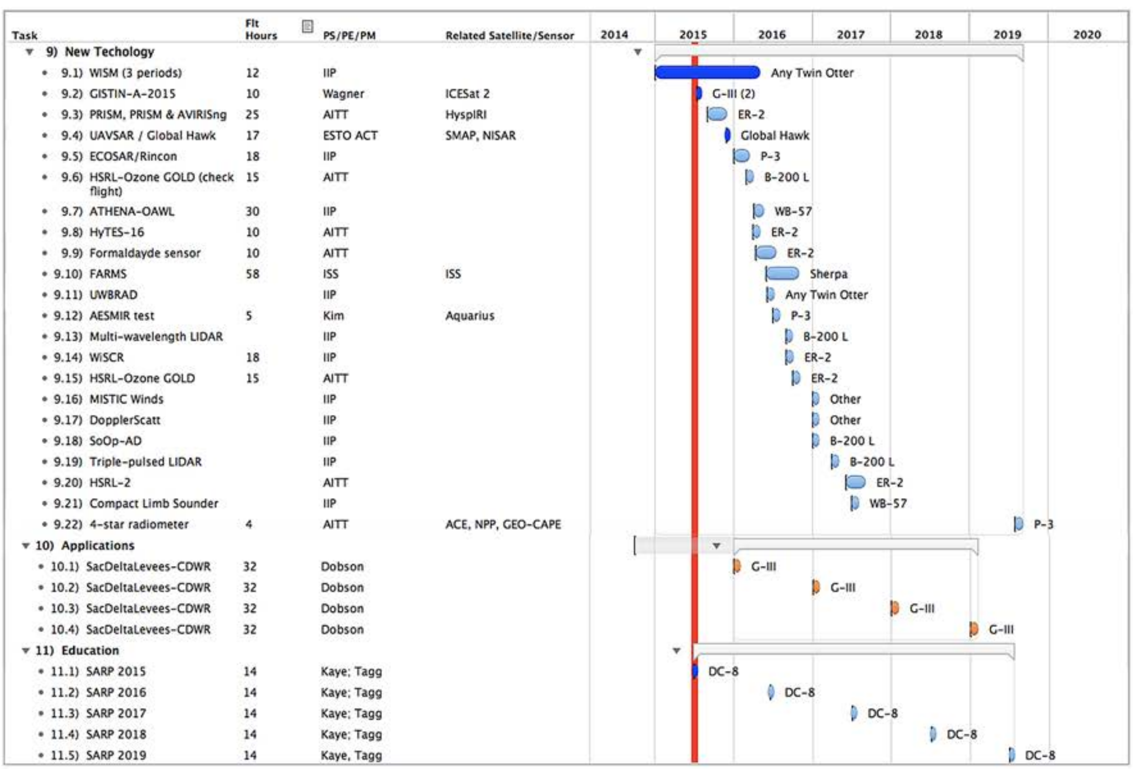
Airborne Science 5 Year Plan by science area (continued)

Task	Flt Hours	PS/PE/PM	Related Satellite/Sensor	2014–2020
4) Water and Energy Cycle				
4.1) Rotating PALS Demo	4	SMAP program	SMAP	DC-3
4.2) SMAPVEX w rotating PALS	50	SMAP program	SMAP	
4.3) AIRSWOT	75	Entin, Lindstrom	SWOT	B-200 D
4.4) Airborne Snow Observatory	50	Entin		A90
4.5) SLAP	11	Entin	SMAP	B-200 L
4.6) SMAPVEX-15-PALS	50	Entin	SMAP	Any Twin Otter
4.7) SMAP UAVSAR-15	30	SMAP program	SMAP	G-III
4.8) AirMOSS Alaska	20	Entin	SMAP	G-III (2)
4.9) Airborne Snow Observatory	50	Entin		A90
4.10) AirMOSS Alaska	20	Entin	SMAP	G-III (2)
4.11) Snow transects (in development)		Entin	SMAP	TBD
4.12) AirMOSS Alaska	20	Entin	SMAP	G-III (2)
4.13) SMAPVEX-16-RPALS	70	SMAP program	SMAP	P-3
4.14) SMAPVEX-16	60	SMAP program	SMAP	Any Twin Otter
4.15) SMAP UAVSAR-16	30	SMAP program	SMAP	G-III
4.16) Snow field campaign (CLPX-like)		Entin		Any Twin Otter
4.17) RZSM - ESA Collaboration	30	Entin	ESA BIOMASS	G-III (2)
4.18) SMAP UAVSAR-17	30	SMAP program	SMAP	G-III
4.19) SMAP UAVSAR-18	30	SMAP program	SMAP	G-III
4.20) SMAP UAVSAR-19	30	SMAP program	SMAP	G-III

Task	Flt Hours	PS/PE/PM	Related Satellite/Sensor	2014–2020
5) Earth Surface & Interior				
5.1) UAVSAR - 15	290	Dobson; Tagg	NISAR	G-III
5.2) Salton Sea mud pots	10	Phillips	HyspIRI / ASTER	SIERRA
5.3) UAVSAR - 16	290	Dobson; Tagg	NISAR	G-III
5.4) UAVSAR - 17	290	Dobson; Tagg	NISAR	G-III
5.5) UAVSAR - 18	290	Dobson; Tagg	NISARI	G-III
5.6) UAVSAR - 19	290	Dobson; Tagg	NISAR	G-III
6) Weather				
6.1) Polar Winds	67	Kakar	CALIPSO, GPM, ADM	DC-8
6.2) PECAN	50	Kaye	NPP, AQUA	DC-8
6.3) NOAA SHOUT	268	Hood		Global Hawk
6.4) HIWC	50	Kakar	GOES I-M, GOES N-P	DC-8
6.5) Tropical Cyclone Intensity	60	Tsui	TRMM, GPM	WB-57
6.6) OLYMPEX (GPM c/v)	100	Kakar, Neeck	GPM	DC-8; UND Citation
6.7) Polar Winds repeat	67	Kakar	ADM / GPM	DC-8
6.8) APR-3 (Durden)	10	AITT	GPM	DC-8
6.9) GOES-R cal/val		Kakar	GOES-R	ER-2
6.10) NOAA SHOUT-16	268	Hood		Global Hawk
6.11) Cloud Experiment	10	Phillips	GPM	C-130
6.12) GPM cal/val		Phillips	GPM	DC-8; UND Citation
6.13) GOES-R cal/val		Kakar	GOES-R	ER-2
7) Earth Venture 1				
7.1) AirMOSS - 15	300	Entin; Tagg	SMAP	G-III (2)
7.2) CARVE - 15	336	CCE; Tagg	OCO-2	Sherpa

Airborne Science 5 Year Plan by science area (continued)





APPENDIX C. Acronyms

ABoVE	The Arctic-Boreal Vulnerability Experiment
ACE	Aerosol-Cloud-Ecosystem
ACT-America	Atmospheric Carbon and Transport-America
ADS-B	Automatic Dependent Surveillance-Broadcast
AFRC	Armstrong Flight Research Center
AGL	Above ground level
AirMOSS	Airborne Microwave Observatory of Subcanopy and Subsurface
AITT	Airborne Instrument Technology Transition
AMPR	Advanced Microwave Precipitation Radiomete
AMSR-E	Advanced Microwave Scanning Radiometer for EOS
ARC	Ames Research Center
ARCTIC COLORS	Arctic – Coastal Land Ocean Interactions
ARMD	Aeronautics Research Mission Directorate
ASCENDS	Active Sensing of CO2 Emissions over Nights, Days and Seasons
ASMLS	Airborne Scanning Microwave Limb Sounder
ASP	Airborne Science Program
ATMS	Advanced Technology Microwave Sounder
ATOM	Atmospheric Tomography Experiment
ATTREX	Airborne Tropical Tropopause Experiment
AVIRIS-ng	Airborne Visible / Infrared Imaging Spectrometer-next generation
AVIRIS	Airborne Visible / Infrared Imaging Spectrometer
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMPEx	Cloud-Aerosol-Monsoon-Philippines Experiment
CARVE	Carbon in Arctic Reservoirs Vulnerability Experiment
CATS	Cloud Aerosol Transport System
CERES	Clouds and the Earth's Radiant Energy System
CLPX	Cold Land Processes Experiment
CORAL	Coral Reef Airborne Laboratory
COSMIR	Conical Scanning Millimeter-wave Imaging Radiometer
COTS	Commercial Off-the-Shelf
CPL	Cloud Physics Lidar

CPR	Cloud Profiling Radar
CrIS	Cross-track Infrared Sounder
CYGNSS	Cyclone Global Navigation Satellite System
DISCOVER-AQ	Deriving Information on Surface Conditions from column and vertically resolved observations relevant to Air Quality
DPR	Dual- frequency Precipitation Radar
ECOSTRESS	ECOSTRESS = Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station
eMAS	enhanced MODIS airborne simulator
EO	Earth Observer
ESD	Earth Science Directorate
ESSP	Earth Science Pathfinder Program
ESTO	Earth Science Technology Office
EV	Earth Venture
EVS	Earth Venture Suborbital
EXPORTS	EXport Processes in the Ocean from RemoTe Sensing
FAA	Federal Aviation Administration
G-LiHT	Goddard's Lidar, Hyperspectral and Thermal
GCAS	GEO-CAPE Airborne Simulator
GEDI	Global Ecosystem Dynamics Investigation
GEO-CAPE	GEOstationary Coastal and Air Pollution Events
GEO-TASO	Geostationary Trace gas and Aerosol Sensor Optimization
GH	Global Hawk
GHG	Greenhouse Gas
GLISTIN	Glacier and Ice Surface Topography Interferometer
GOCI	Geostationary Ocean Color Imager
GPM	Global Precipitation Measurement
GRACE	Gravity Recovery and Climate Experiment
GSFC	Goddard Space Flight Center
HDSS	High Definition Sounding System
HIRDLS	High resolution dynamics limb sounder
HIWRAP	High-Altitude Imaging Wind and Rain Airborne Profiler
HS3	Hurricane and Severe Storm Sentinel
HSRL	High Spectral Resolution Lidar

HyspIRI	Hyperspectral Infrared Imager
HyTES	Hyperspectral Thermal Emission Spectrometer
ICCAGRA	Interagency Coordinating Committee for Airborne Geoscience Research and Applications
IIP	Instrument Incubator Program
IIR	Imaging Infrared Radiometer
InSAR	Interferometric synthetic aperture radar
ISS	International Space Station
KaSPAR	Ka-band SWOT Phenomenology Airborne Radar
KDP-A	Key Decision Point-A
LaRC	Langley Research Center
LCLUC	Land Cover Land Use Change
LIS	Lightning imaging sensor
LVIS	Laser Vegetation Imaging Sensor
MABEL	Multiple Altimeter Beam Experimental Lidar
MACPEX	Mid-latitude Airborne Cirrus Properties Experiment
MAS	MODIS Airborne Simulator
MASTER	MODIS/ASTER Airborne Simulator
MISR	Multi-angle Imaging SpectroRadiometer
MLS	Microwave limb sounder
MODIS	Moderate-Resolution Imaging Spectroradiometer
MTS	Mission Tool Suite
NAAMES	North Atlantic Aerosols and Marine Ecosystems Study
NAS	National Airspace
NAST	NPOESS Airborne Sounder Testbed
NCAR	National Center for Atmospheric Research
NIR	Near Infrared
NISAR	NASA-ISRO SAR
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
NSF	National Science Foundation
OCI	Ocean Color Instrument
OCO	Orbiting Carbon Observatory

OIB	Operation IceBridge
OMG	Ocean Melting Greenland
OMI	Ozone monitoring instrument
OMPS	Ozone Mapper and Profiler Suite
ORACLES	Observations of Aerosols Above Clouds and their Interactions
PACE	Pre-Aerosol-Cloud-Ecosystem
PALS	Passive Active L-and S-band Sensor
PRISM	Portable Remote Imaging Spectrometer
RSP	Research Scanning Polarimeter
SABOR	Ship-Aircraft Bio-Optical Research
SAGE	Stratospheric Aerosol and Gas Experiment
SAR	Synthetic Aperture Radar
SatCom	Satellite Communications
SEAC4RS	Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys
SIMPL	Slope Imaging Multi-polarization Photon-counting Lidar
SLAP	Scanning L-band Active Passive
SLI	Sustained Land Imaging
SMAP	Soil Moisture Active Passive
SMD	Science Mission Directorate
SOFRS	Science Operations Flight Request System
SWIM	System Wide Information Management
SWOT	Surface Water and Ocean Topography
TBD	To be determined
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TES	Tropospheric emission spectrometer
UAS	Unmanned Aircraft System
UAVSAR	Unmanned Aerial Vehicle Synthetic Aperture Radar
UNOLS	University-National Oceanographic Laboratory System
UTLS	Upper troposphere / lower stratosphere
VIIRS	Visible Infrared Imager Radiometer Suite
WFC	Wide Field Camera
WFF	Wallops Flight Facility

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