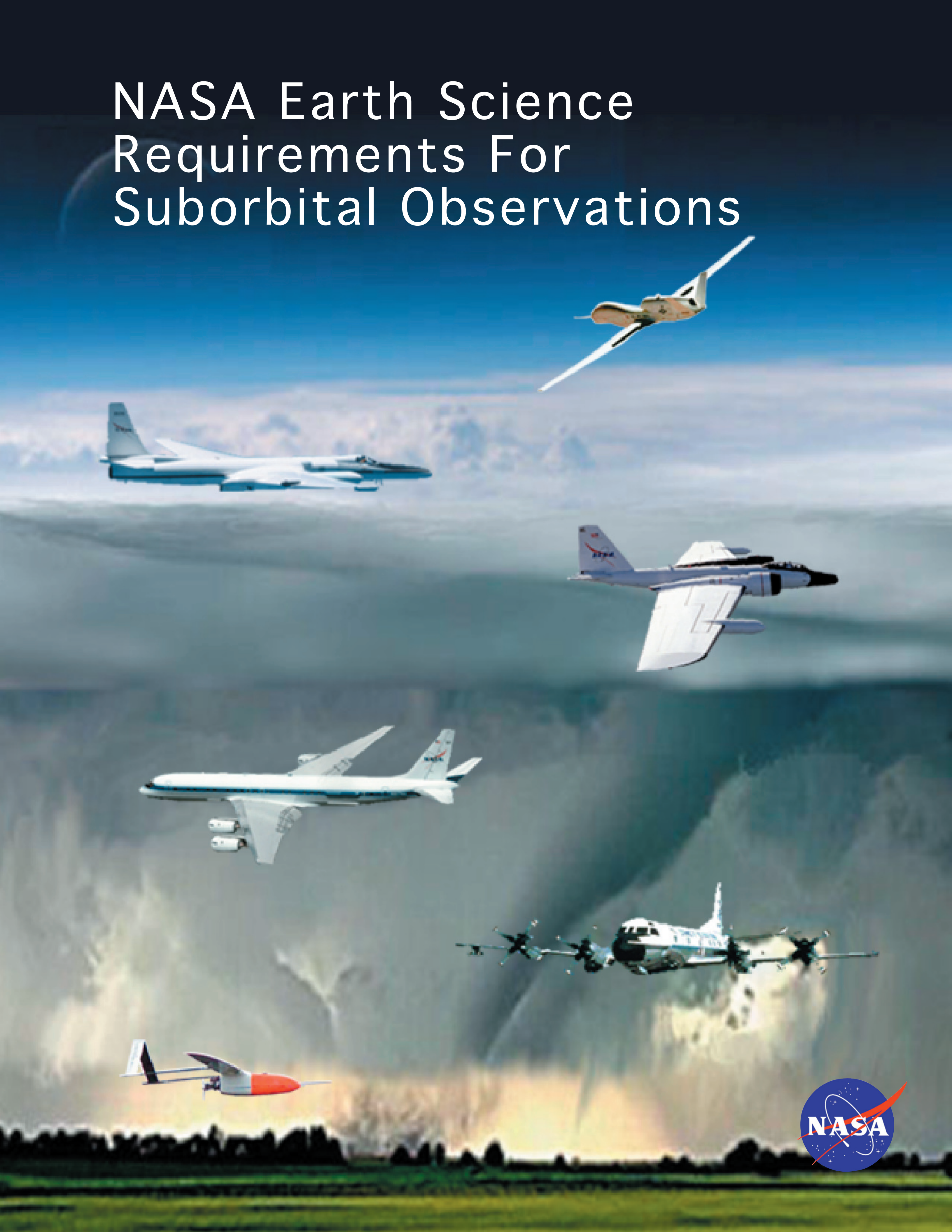
NASA Earth Science Requirements For Suborbital Observations



NASA Science Mission Directorate
Earth Science Division

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http://suborbital.nasa.gov

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1. Introduction and Program Description

The NASA Science Mission Directorate (SMD) Suborbital Science Program (SSP), also known as Airborne Science, is responsible for providing aircraft systems that complement NASA satellite mission goals and enable new and unique measurements of Earth system processes. From the suborbital vantage point, requirements generally range from 100 to 100,000 feet in flight altitude providing local to regional coverage. Scientists are able to gather unique high resolution science data (spatial, temporal, and spectral) of the earth surface and atmosphere. In addition, airborne science is an important stepping stone to future satellite missions through the development and testing of new technologies and processes, while providing mission experience for the next generation of principal investigators and instrument engineers.

Flight missions conducted by SSP support three primary science objectives and it is from these three categories of missions the SSP derives its top-level requirements:

1. To calibrate satellite sensors and develop or validate retrieval algorithms;
2. To collect in situ measurements and high resolution imagery for Earth science process studies; and
3. To develop and test new instruments and future satellite mission concepts

An overarching objective of the program is to provide a well-defined, consistent set of technologies to meet sciences' long term measurement requirements, while enabling new measurements through the applications of new technologies. NASA's airborne assets include highly modified aircraft that provide view ports, inlets, power, data systems, and communications capabilities needed to perform Earth science missions.

Requirements for suborbital observations originate from three primary communities: the NASA Earth Science Division (ESD) Research and Analysis program, NASA satellite missions, and technology development programs such as the Earth Science Technology Office's (ESTO) - Instrument Incubator Program (IIP) and Advanced Information Systems Technology Program (AIST). By understanding these different customers for their unique needs, the Program is best able to match assets and capabilities to specific measurement requirements. The primary document that drives ESD Program content is the NASA Science Plan, most recently updated in 2007. This document provides an overview of future missions and science goals. Information on ESD research focus areas is gathered through the Research Plan (2005), interviews, solicitations, conferences, publications, and workshops. Another important source for understanding Earth science needs is the community-developed roadmaps and the NRC decadal survey which outlines steps needed to achieve important goals in each discipline. Each step represents new observations, reductions in uncertainty, and improved model fidelity.

Frequent interaction with Mission scientists and principal investigators provides a critical pathway for understanding mid- to long- term science requirements. The SSP 5-yr schedule provides an annual update on the near to mid-term science mission requirements for the program from the agency's science disciplines and flight projects (See Appendix I & II). The schedule is developed through inputs from the six ESD science focus area program managers and scientists. The schedule documents major campaigns in each science discipline, sensor development and testing efforts, interagency science campaigns, and calibration and validation needs for space mission.

Additional sources of data for this report include mission science team meetings, peer-reviewed journal publications, community white papers that outline proposals for future science campaigns, conference presentations and proceedings. The Program also conducted interagency workshops from 2002-2005 that focused on suborbital mission concepts in the 2015-2020 time frame.

Altitude versus endurance is one of several possible analyses for understanding future science mission requirements as a function of aircraft needs. We intend to use altitude vs. endurance in this assessment as it is applicable across the scope of our missions, and provides the most basic level of requirements against which we can compare our capabilities. Future analyses that quantify range, volume, weight, power and other evaluation parameters will be added to updates to this document after we have evaluated the utility of these metrics for understanding science requirements.

This report summarizes the science requirements that drive the decisions which determine the investments and assets that SSP uses to facilitate NASA science. This requirements collection, validation, analysis and communication will ensure that Airborne Science is providing the right selection of government and non-government aircraft and subsystems for NASA science missions for the best overall value. The SSP requirements analysis process was developed to ensure sustained access to unique, highly modified, science capable aircraft, in addition to being a portal to specialized commercial, university and interagency aircraft providers as science needs warrant.

2. Level 1 Requirements

NASA Earth science observational requirements are developed by matching observations (i.e., active, passive and in situ sensors) with the measurements needed to answer NASA science questions developed by the communities in each science focus area. Requirements for suborbital observations and the selection of aircraft are primarily determined by the concept-of-operations needed for payloads to gather scientifically useful data. Different customers have very different requirements and uses for suborbital observations primarily depending on the degree to which observations must be coordinated with earth system phenomenon such as an evolving air mass, a particular ground track, specific vertical profiles, or coordination with one or more aircraft and satellite.

This report decomposes requirements as a function of primary airborne science measurement types to ensure traceability to our user community, and to document and explore both the similarities and differences between different types of missions and requirements for the measurement goals. This section starts with the discussion of how airborne observations are vital in the development and testing of new sensors and measurement systems followed by satellite calibration and validation requirements for airborne measurements and concludes by analyzing the requirements of the six NASA SMD ESD science focus areas.

2.1 Provide reliable airborne systems for developing and testing new sensor systems in preparation for future satellite missions

Assets from SSP are required to provide platform systems for testing sensors that are developed under the NASA Earth Science Technology Office (ESTO), the NASA Small Business Innovative Research (SBIR) Program and other technology development projects. Many of these sensors are ultimately destined for satellite systems, but they require testing and data product validation before committing to launch. The main purpose of the NASA ESTO Instrument Incubator Program (IIP) is to identify, develop and, where appropriate, demonstrate new measurement technologies that reduce the risk, cost, size and development time of Earth observing instruments, and/or to enable new observation measurements.

Table 2.1 lists those IPP instruments with estimated flight dates and possible aircraft for test flights. Each of these instrument teams provides SSP with data on the necessary volume, power, and communications requirements for the sensor. In addition, the flight regime for the measurement is included to understand the altitude, endurance, and flight profiles required for science observations. For most sensor development efforts, initial flights are short in duration to test out the systems which may be different from the nominal concept of operations.

Instrument Incubator Project	**PI & Organization**	**Satellite or Science Supported**	**Flight Altitude Required**	**Flight Plan/Aircraft Requirements**
Micro-cavity spectrometer	Anderson, Harvard	MODIS/AIRS validation	surface to 50,000 ft.	2008, high alt. long duration
Global Ozone Lidar Demonstrator (GOLD)	Browell, LaRC	Column O_3; DSR	mid/upper-trop	12/08, high alt. long duration
Multi-functional Fiber Laser Lidar (MFLL)-ice mapping	Dobbs, ITT Industries	Greenland ice sheet mass balance; DSR	200 ft AGL	10/07-8/08, long duration
Tropical Wind Lidar Technology Experiment (TwiLiTE)	Gentry, GSFC	Tropopause transition layer; DSR	60,000 ft	2/07-6/08, vertical profiles
Multi-beam, fiber laser altimeter= swath imaging multi-polarization photon-counting Lidar (SIMPL)	Harding, GSFC	Surface topography; LIST satellite; DSR	20,000 ft; and 50,000 ft.	2/08-4/08, multiple platforms
High-altitude imaging wind and rain Airborne profiler (HIWRAP)	Heymsfeld, GSFC	QuickSCAT; atmospheric transport; DSR	50,000+ ft	5/08-8/08, over hurricanes
HSRL + DIAL	Hostetler, LaRC	Aerosol and cloud profiles; DSR	28,000 ft	12/08
DIAL for CO_2 profiling	Ismail, LaRC	OCO; DSR	30,000	10/08
Laser Sounder for Global CO_2	Abshire: GSFC	OCO; carbon cycle studies; DSR	55,000	12/07 - 8/08
Global Ice Sheet Interferometric Radar (GISIR)	Jezek, Ohio State	Imaging through polar ice sheets; DSR	30,000 - 40,000 ft.	11/06, 11/07, etc.
Coherent Doppler wind lidar	Kavaya, LaRC	Weather; DSR	ultimately 60,000 ft, first tests on DC-8	2/09
In situ Net Flux within the atmosphere of Earth (INFLAME)	Mlynczak, LaRD	Net radiative flux	profiling from 10 to 40k ft	2007, 2008, 2009
Radar Interferometer for ice mapping	Moller, JPL	Ice tropography; DSR	40,000 ft	8/08
Pathfinder Advanced Radar Sounder (PARIS)	Raney, Johns Hopkins	Mapping ice sheet bottom topography; DSR	30,000 ft	2007
RASL (Raman Airborne Spectroscopic Lidar)	Whiteman, GSFC	Lidar combining many measurements; DSR	25,000-60,000 ft	8/07 Multiple Platforms
UAVSAR	Scott Hensley, JPL	Interferograms of faults and other geologic areas of interest	Precise repeated flight lines within 10m	2007-2008
Geostationary Imaging Fabry-Perot Interferometer (GIFS)	J-H Yee, APL; Hostetler, Pitts LaRC	atmospheric mapping	high altitude	2008
Tropospheric Trace Species Sensing Fabry-Perot Interferometer (TTSS-FPI)	Larar LaRC; Smith Hampton Univ./Univ. Wis.	Trace species in the troposphere; DSR	high altitude required	2006-2008

Table 2.1: Instrument Test Flight Plans for current Instrument Incubator Program projects. DSR indicates that the mission supports or can potentially support observations recommended by the Decadal Survey for future NASA Earth Science satellite missions.

2.2 Provide observations that enable the calibration of satellite sensors and validation of retrieval algorithms for science data products

NASA satellite mission data products are used to drive earth science models, enabling prediction of Earth's changing climate. These products such as land cover characteristics, column concentrations of gases, and upwelling/downwelling radiation are derived by interpreting radiances or signal processing. In order to be useful in models, scientists validate satellite-derived data products using a combination of remotely-sensed and in-situ atmospheric measurements obtained from SSP airborne platforms carrying payload sensors that are well characterized and calibrated in the laboratory.

Suborbital platforms support space flight missions by providing NIST-traceable calibrated spectro-radiometric imagery, in situ sampling, and ancillary data that enable calibration/validation (cal/val) and improve data reduction and product generation for the satellite-based measurement systems. Numerous past field experiment campaigns underflying satellite sensors have demonstrated the tremendous benefit toward spaceborne measurement system cal/val achievable from implementation of NASA SSP assets. The combination of in-situ and remote measurements enabled by the SSP, and the scientific community, provide the best possible characterization of the terrestrial surface, atmosphere, and clouds that are being observed within the satellite sensor instantaneous fields of view (IFOVs), all of which must be properly addressed to enable cal/val to the levels being dictated by future science measurement requirements. Furthermore, validation of the satellite sensor's directly-measured radiances, the products from which all other higher-order geophysical products are derived, is best achieved through implementation of airborne sensors on high-altitude platforms. When optimally instrumented, and with proper flight profile design, the resultant airborne measurements can provide the appropriate spatial & temporal coincidence/context needed to best emulate satellite-based measurements for the instrument being validated. The high spectral and spatial resolution obtainable from the aircraft sensor radiance data can be spectrally and spatially convolved, respectively, to simulate what should be measured by the spatially and temporally coincident satellite observations during overpass events. The much higher spatial resolution of the aircraft sensor data can play an important role in validating satellite-derived data products under the condition of scene non-uniformity (i.e., due to variable surface, atmosphere, or cloud conditions) within the satellite sensor footprint.

Each mission has different requirements depending on whether active or passive remote sensing is called for, and whether surface or atmospheric phenomenon are being observed or measured. Figure 2.1 is the current timeline of Earth Science missions. In Table 2.2 is a similar list of upcoming NASA Earth science satellite-based missions and the role of SSP to support them.

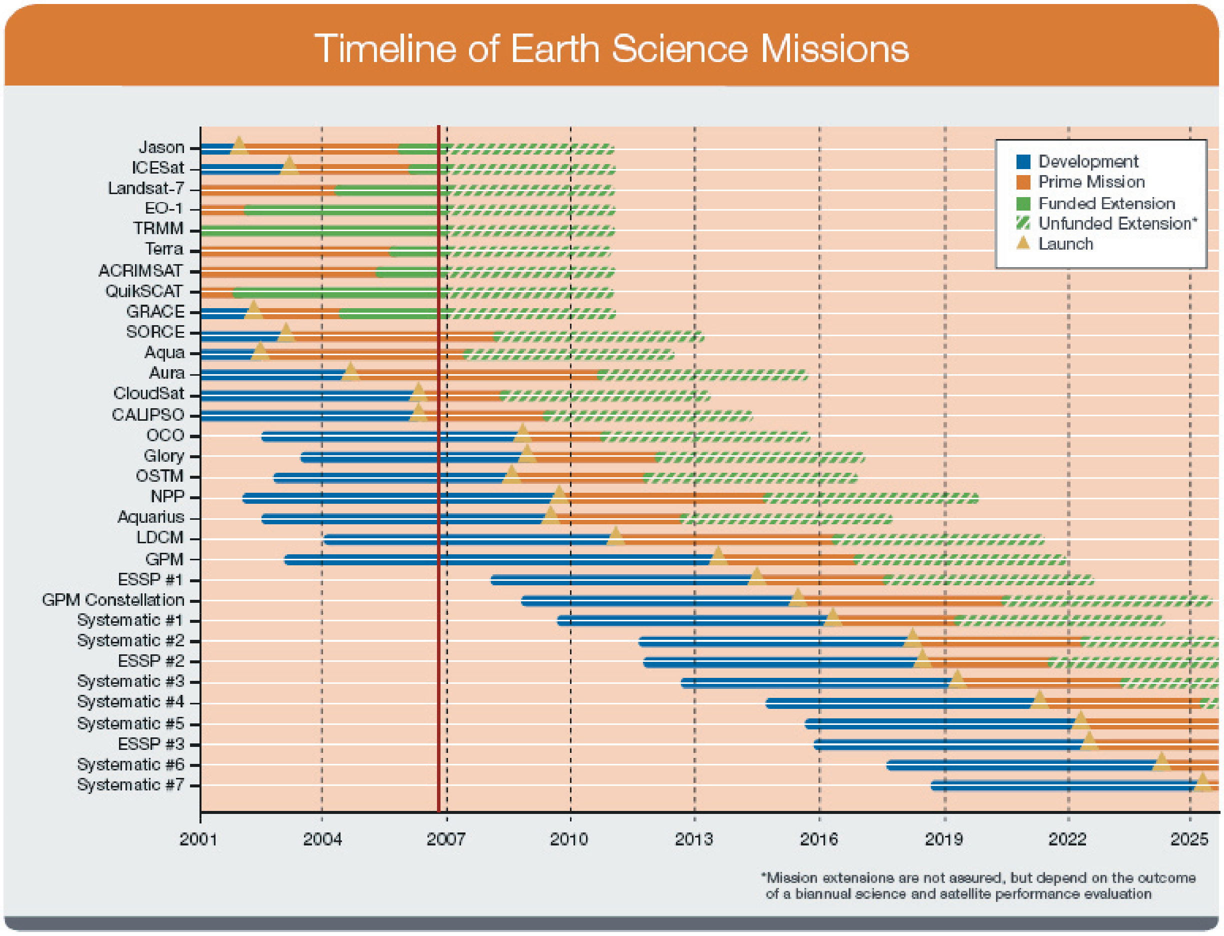


Figure 2.1: Current and future NASA Earth Science Missions (source: NASA Science Plan, 2007).

Mission	**Objective**	**Suborbital role**
Glory	Determine atmospheric aerosol properties from the polarization of backscattered solar radiation. Also, measure total solar irradiance.	In situ sampling and imaging from ground to 50,000 ft. Remote sensing from mid and high altitudes to simulate data.
OSTM (Ocean Surface Topography Mission)	Determine ocean surface topography to study ocean circulation and its environmental applications (follow-on to Jason; cooperative with France, EUETSAT, and NOAA).	No current defined suborbital role
OCO (Orbiting Carbon Observatory)	Provide space-based observations of atmospheric carbon dioxide, the principal anthropogenic driver of climate change.	High altitude satellite simulation data; mid-to high altitude in situ measurements CO_2, CH_4, CO; low altitude CO_2 flux measurements
NPP (NPOESS Preparatory Project)	Extend key measurements in support of long-term monitoring of climate trends and global biological activity NPP extends the measurement series Terra and Aqua and provides a bridge to MPOESS	Provide platforms for cal/val with simulator sensors in-situ measurements requiring low, medium and high altitude regimes.
LDCM (Landsat Data Continuity Mission)	Extend the Landsat record of multispectral, 30-m resolution, seasonal, global coverage of Earth's land surface (joint with USGS).	High spatial resolution imagery over different land cover types to refine retrieval algorithms
Aquarius	Measure global sea surface salinity and ocean circulation (cooperative mission with Argentina).	Provide satellite data simulation from airborne radar instruments
GPM (Global Precipitation Measurement mission)	Monitor precipitation globally (joint with Japan and other international partners, building on the success of TRMM)	Airborne measurement of clouds, aerosols, snow, and rain from lidar and radar
NPOESS	A joint program between NOAA, DoD, and NASA that will provide operational long-term collection of climate data for oceans, land and atmosphere	Providing airborne platforms for sensor simulators, and will provide cal/val data for imagers and sounders.

Table 2.2: NASA Earth Science Satellite Programs and plans for suborbital observations

2.3 Provide observations of earth system processes that enable local- to global-scale analysis

Research and analysis projects sponsored by the NASA SMD Earth Science division support six science focus areas: Atmospheric Composition, Carbon Cycle & Ecosystems, Climate Variability and Change, Earth Surface & Interior, Water & Energy Cycle, and Weather. Each of these science focus areas are driven by a series of specific science questions aimed at providing a greater understanding of how the earth functions as a system of interrelated processes.

The main objectives of NASA Earth Science research are to:

1. Understand and improve predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition.
2. Enable improved predictive capability for weather and extreme weather events.
3. Quantify global land cover change and terrestrial and marine productivity and improve carbon cycle and ecosystem models.
4. Quantify the key reservoirs and fluxes in the global water cycle and improve models of water cycle change and fresh water availability.
5. Understand the role of oceans, atmosphere, and ice in the climate system and improve predictive capability for its future evolution.
6. Characterize and understand Earth surface changes and variability of Earth’s gravitational and magnetic fields.
7. Expand and accelerate the realization of societal benefits from Earth system science.

Each of these six focus areas represents a diverse set of communities and each has different requirements for suborbital observations. NASA satellite missions are the primary source of information that drives the research, and airborne measurements are critical to developing, validating, and improving the data products generated by these missions and are important for providing new observations that confer an understanding of the local to regional processes underlying these global datasets.

2.3.1 Atmospheric Composition

The overarching goal of the Atmospheric Composition Focus Area is geared to providing an improved forecasting capability for the recovery of stratospheric ozone and its impacts on surface ultraviolet radiation, the evolution of greenhouse gases and their impacts on climate, and the evolution of troposphere ozone and aerosols and their impacts on climate and air quality. This focus area is composed of programs in stratospheric chemistry, radiation, and tropospheric chemistry.

Research in this discipline is guided by the following science questions:

- How is atmospheric composition changing?
- What trends in atmospheric constituents and solar radiation are driving global climate?
- How do atmospheric trace constituents respond to and affect global environmental change?

- What are the effects of global atmospheric chemical and climate changes on regional air quality?
- How will future changes in atmospheric composition affect ozone, climate, and global air quality?

To answer these questions scientists need to develop a quantitative understanding of changes in atmospheric composition at the timescales over which they occur and to understand forcings (anthropogenic and natural) that drive the changes. Scientists are also interested in the effects of atmospheric trace constituents on global climate, as well as the effects of global atmospheric chemical and climate changes on regional air quality.

Over the next five years, this program seeks to better characterize, understand and model the transport and evolution of ozone, aerosols, and greenhouse gases globally. Scientists in this focus area rely on data from UARS, TOMS, QuickTOMS, OMI, AURA satellites to monitor ozone, trace chemicals and aerosol optical thickness and distribution in the atmosphere. Together these sources of data inform investigators into the processes responsible for the emission, uptake, transport, and chemical transformation of ozone and precursor molecules associated with its production in the troposphere and stratosphere as well as its destruction in the stratosphere.

Information on concentrations of ozone, and the size and distribution of aerosols derived from satellites are compared with measurements from aircraft to improve the accuracy and precision of global data products. Suborbital measurements are needed throughout the atmospheric column from the troposphere through the stratosphere to gather data on the formation, properties, and transport of ozone, precursor molecules and aerosols in the Earth’s troposphere and stratosphere.

For atmospheric chemistry missions, the following general requirements must be met:

- In situ sampling requires sampling at various altitudes (vertical and horizontal profiling) during a flight to understand distribution, transport and source/sink relationships.
- Validation of satellite column measurements needs to include measurement above the majority of atmospheric water vapor to reduce uncertainty associated with atmospheric absorption, reflection, and scattering, in addition to measurements in the atmosphere from the surface to 100k ft.

Type	Timeframe	Suborbital Program support/remarks
Satellite Cal/Val missions		
EOS (AURA, AQUA, TERRA)	2006-2008	Pre- and post-launch Cal/Val
OCO	2008-2010	Cal/val
GLORY	2009-2010	Cal/val
AQUARIUS	2009-2010	Cal/val
NPOESS	2011	Cal/val
Calipso/Cloudsat	2006 +	Cal/val
ACE (Canada)		
Schiamachy		
MIPAS (EU)		
New Airborne Sensor development		
HSRL	2006-7	A-Train validation, aerosols
IIP - Harvard water	2006-7	
Laser sounder for CO2	2007-8	Global measurement demo
GOLD	2006	Airborne Ozone Lidar
IIP - HSRL and DIAL Lidar	2008	Ozone, Aerosols
Airborne Process studies		
TC-4	2007 (Costa Rica); 2010 (Guam)	Validates A-Train, plus process studies: trace species; Pollution chemistry in the Arctic
ARCTAS / POLARCAT	2008 (Arctic)	Stratospheric chemistry
Global Hawk / decadal survey proposal	2009	

Table 2.3 Summary of select future atmospheric composition SSP missions

- Multiple aircraft are required for month+ campaigns to meet the disparate Payload sampling requirements.
- Large payload capacity for multiple chemistry payloads
- Over-the-horizon data downlink in real-time for aircraft position, instrument status and data samples to allow for real time flight track modifications
- Situational awareness for science team: location of aircraft at all times, along with instrument status and real-time data; coupled with weather and other conditions at flight locations; satellite track overpass timing assists with calibration and validation studies

Figure 2.2 shows the altitude and endurance characteristics for all the atmospheric chemistry missions considered for both the near and far-term.

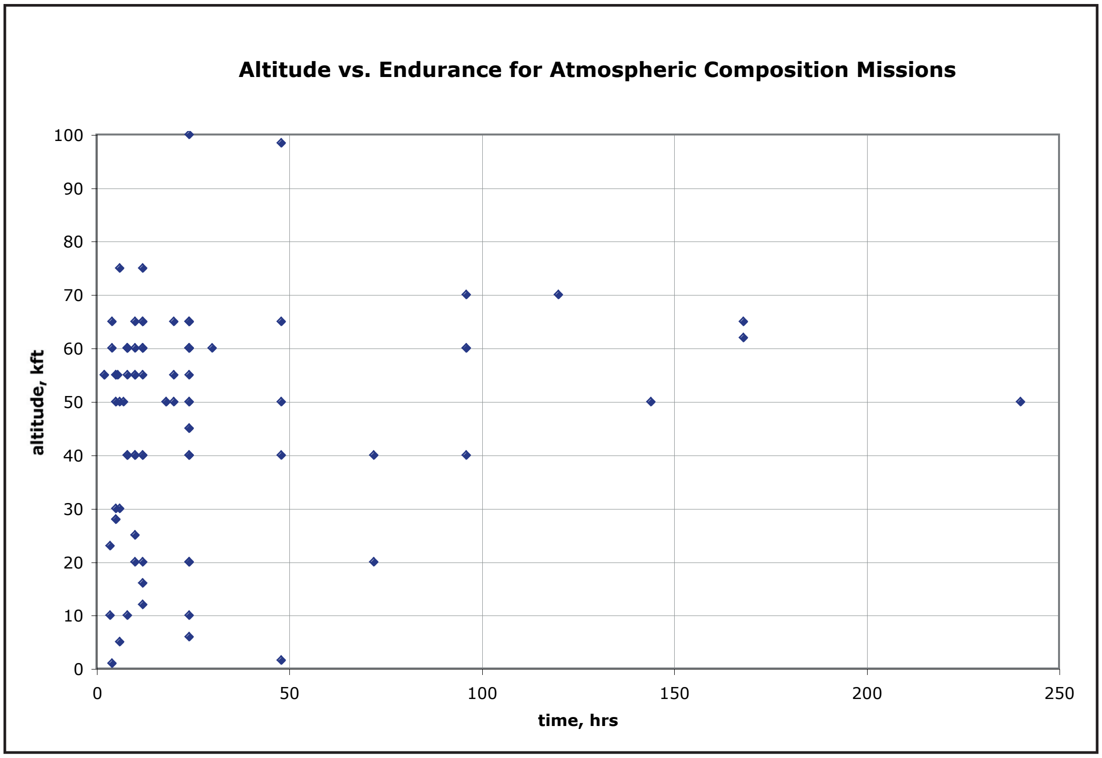


Figure 2.2 Select science airborne measurement requirements as a function of altitude and endurance based upon the 2006 5-yr plan, interviews with Program and Project Managers and scientists, and NASA, NOAA, DOE workshops convened in 2004 and 2005.

2.3.2 Carbon cycle and ecosystems

Environmental change and human activities alter Earth's ecosystems and the biogeochemical cycles that are critical to the habitability of our planet. In addition to providing habitat and natural resources while nurturing crucial biodiversity, ecosystems interact with numerous geochemical and physical systems to maintain the global carbon cycle and its control over changes in atmospheric CO_2 and CH_4 and thus climate. Over the past two centuries, fossil fuel emissions and other human activities increased atmospheric CO_2 by 30% and CH_4 by 150% to concentrations unprecedented over the past 400,000 years.

Ecosystems respond continuously to environmental variability and change as well as to numerous disturbances by human activities and natural events. Responses range from changes in ecosystem distribution and extent; impacts on natural resources (e.g., food, fiber, fuel, and pharmaceutical products); ecosystem services (e.g., cleaning of water and air, climate and weather regulation, carbon and nutrient storage and cycling, habitat, maintenance of water resources) to variations in fundamental processes including exchanges of energy, momentum, trace gases, and aerosols with the atmosphere that in turn influence climate.

Research in the Carbon Cycle and Ecosystems Focus Area addresses the following science questions:

- How are global ecosystems changing?
- What changes are occurring in global land cover and land use, and what are their causes?
- How do ecosystems, land cover and biogeochemical cycles respond to and affect global environmental change?
- What are the consequences of land cover and land use change for human societies and the sustainability of ecosystems?
- What are the consequences of climate change and increased human activities for coastal regions?
- How will carbon cycle dynamics and terrestrial and marine ecosystems change in the future?

Research in this focus area seeks to quantify global productivity, biomass, carbon fluxes, and changes in land cover; to document and understand how the global carbon cycle, terrestrial and marine ecosystems, and land cover and use are changing; and to provide useful projections of future changes in global carbon cycling and terrestrial and marine ecosystems for use in ecological forecasting and for improving climate change predictions.

In partnership with the atmospheric scientists, carbon cycle scientists seek to understand the transport of carbon from the atmosphere into plant matter, and to understand how this process interacts with land use and changes to the climate controls on productivity. Over the next five years scientists in this area will be developing the next generation of Landsat imagers, validating the Orbiting Carbon Observatory, and continuing to explore the power of hyperspectral imagery and lidar for vegetation type and structure. The primary satellites used terrestrial component of this discipline are MODIS, Landsat, Hyperion, and other land passive optical imagers. Coupling these measurements with structure data from lidar and radar enables refinement of primary productivity models and ultimately carbon exchange between the Earth surface and the atmosphere.

Type	Timeframe	Suborbital Program support/remarks
Satellite Cal/Val missions		
Aqua	2002+	Cal/val
Terra	2000+	Cal/val
EO-1	2000+	Cal/val
OCO	2008	Orbiting Carbon Observatory - pre-launch algorithm development
NPP	2009	NPOESS Preparatory project
LDCM	2014	Landsat data continuity mission - Operational Land Imager cal/val
New Airborne Sensor development		
Autonomous modular sensor	2006-7	Wildfire, ocean color, vegetation
Laser sounder for CO2	2007-8	Global measurement demo
Waveform Lidar and compact hyperspectral imager	2008	Vegetation
Airborne Process studies		
AVIRIS - Hawaii	2007	Imagery
AVIRIS - CONUS	2008-2009	Imagery
ARCTAS	2008 (Arctic)	Arctic Haze
NACP	2008-2009	North American carbon budget
Southern Ocean	2010	Carbon dioxide flux at ocean surface

Table 2.4: Summary of select future carbon cycle science missions

For carbon cycle and ecosystems missions, the following general requirements must be met:

- Medium altitude is suitable for many missions
- Higher altitude is desirable for validation of satellite measurements
- Vertical profiling is required for some missions
- Very low altitude measurements are required for flux measurements between vegetation and the tropopause
- In situ sampling and remote sensing
- Over-the-horizon data downlink in real-time
- Situational awareness for science team: location of aircraft at all times, along with instrument status and real-time data; coupled with weather and other conditions at flight locations; satellite tracks

Figure 2.3 indicates the altitude and endurance characteristics of carbon cycle and ecosystem missions, including proposed local and regional air pollution studies.

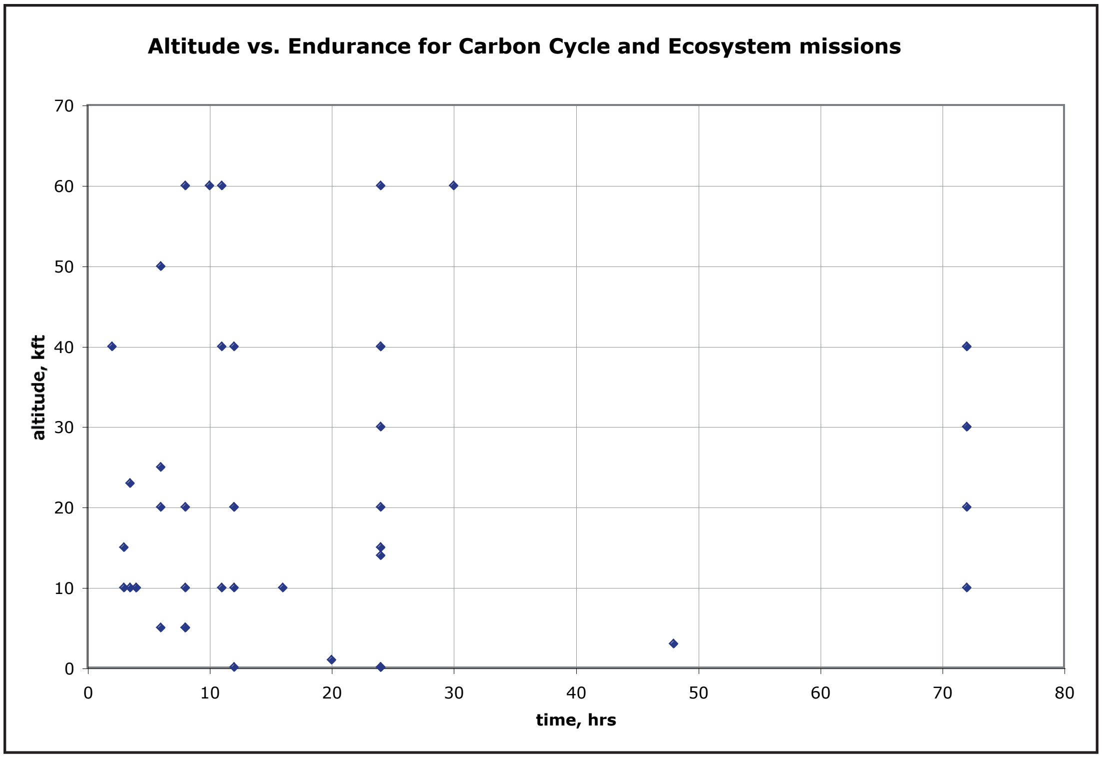


Figure 2.3: Select science measurement requirements as a function of altitude and endurance for carbon and ecosystems missions.

2.3.3 Climate Variability and Change

NASA's role in characterizing, understanding, and predicting climate variability and change focuses on global observations of the more slowly responding components of the system (primarily oceans and ice), naturally occurring processes and human activities that affect climate, and their interactions within the Earth system. The Climate Variability and Change Focus Area address the following major science questions:

Research in the Climate Variability and Change Focus Area addresses the following science questions:

- How is the global ocean circulation varying on interannual, decadal, and longer time scales?
- What changes are occurring in the mass of the Earth's ice cover?
- How can climate variations induce changes in the global ocean circulation?
- How is global sea level affected by natural variability and human-induced change in the Earth system?
- How can predictions of climate variability and change be improved?

Current satellite capabilities that support this focus area include global measurements of sea surface topography, ocean vector winds, ice topography and motion, and mass movements of the Earth's fluid envelope and cryosphere. Critically-needed new measurements include sea-ice thickness, sea-ice snow cover, decadal change in ice mass over land, and sea-surface salinity. Table 2.5 provides a summary of future climate change missions.

Type	Timeframe	Suborbital Program support/remarks
Satellite Cal/Val missions		
ICESat	Since 2003	Polar Ice sheet elevations, low and medium altitude
NPP	2009	NPOESS Preparatory project, pre-launch algorithm development
Aquarius	2009	Sea salinity, cal/val
New Airborne Sensor development		
MFLL - Ice mapping	2007-2008	Fiber laser lidar for ice sheet topography
Laser Altimeter	early 2008	Multi-beam laser altimeter for ice sheet Global ice sheet interferometric radar
GISIR (Greenland)	11/06, 11/07, etc.	Ka radar for ice topography
PARIS	TBD	Radar ice sounder
Airborne Process studies		
Arctic Ice Mapping (AIM) Greenland	2007, 2008	Aeronomy of Ice in the Mesosphere (Polar Mesospheric clouds)
AIM Antarctica	2007-8	Global Ice Sheet mapping orbiter - base of ice
GISMO Greenland	2007-8, 2009	Sensor testing
GISMO Antarctica	2008	Sensor testing
Himalayan ATM	2008	
ARCTAS - POLARCAT (IPY)	2007-8	Arctic Haze (chemical and physical composition)

Table 2.5: Summary of select future climate variability and change missions and nominal SSP function.

For Climate Variability and Change missions, the following general requirements must be met:

- Medium altitude is suitable for many missions (25,000 to 40,000 ft)
- Very low altitude is required for ice measurements
- Stable, well characterized flight paths for repeat transects
- Vertical stacking for some missions
- Long duration for diurnal cycles
- Over-the-horizon data downlink in real-time, including over polar regions
- Situational awareness for science team: location of aircraft at all times, along with instrument status and real-time data; coupled with weather and other conditions at flight locations; satellite tracks

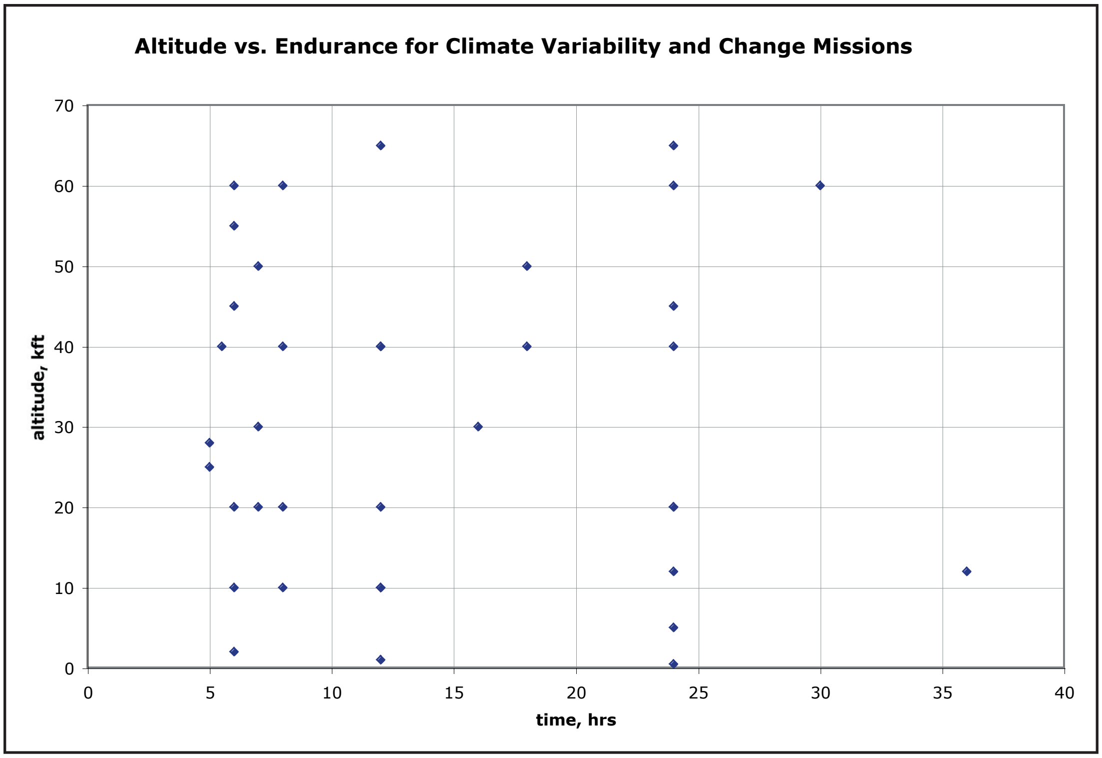


Figure 2.4: Select science measurement requirements as a function of altitude and endurance for climate variability and change missions.

2.3.4 Earth Surface and Interior

The overarching goal of the Earth Surface and Interior focus area is to assess, mitigate and forecast natural hazards that affect society, including such phenomena as earthquakes, landslides, coastal and interior erosion, floods and volcanic eruptions. The path to prediction includes comprehensively recording and understanding the variability of surface changes controlled by two types of forces: external such as climate; and the internal forces that are in turn driven by the dynamics of the Earth's interior.

The Earth Surface and Interior Focus Area promotes the development and application of remote sensing to address the questions:

- How is the Earth's surface being transformed by naturally occurring tectonic and climatic processes?
- What are the motions of the Earth's interior, and how do they directly impact our environment?
- How can our knowledge of Earth surface change be used to predict and mitigate natural hazards?

In order to produce a predictive capability, observations of the Earth's transformation, must be modeled, interpreted, and understood. Remote sensing empowers scientists to measure and understand subtle changes that reflect the response of the Earth to volcanic eruptions, earthquakes, landslides, and sea-level change as well as the climatic forces that sculpt the Earth's surface. A key observational strategy is to move towards geodetic and thermal imaging of the precise metrology of Earth's surface and its changes through lidar, radar constellations, and optical arrays. Imaging coupled with geopotential field measurements will play a primary role in understanding the dynamics of the Earth's surface and interior.

Optical and geodetic imaging using radar and Lidar from aircraft plays a critical role in defining the land surface to sub-meter precision to search for precursory events and to understand the Earth's surface response to both the fluid envelope and interior forces. Airborne observations also enable the development of a stable terrestrial reference frame to better than a millimeter per year, the realization of topography and topographic change to sub-meter precision, and an understanding of changes in the Earth's angular momentum and gravity field are critical to accomplishing focus area goals. These data products provide accurate measures of changes in the Earth, including sea-level change, polar mass balance, and land subsidence.

Scientists in this focus area make use of data from GRACE, ASTER, MODIS, Landsat and Hyperion. Suborbital missions are typically used to provide high resolution thermal imagery of faults, Lidar and SAR data to detect deformation and provide input to digital elevation models, and for testing new sensors such as UAVSAR. The other area of Earth Surface and Interior research requiring suborbital assets is the monitoring of volcanoes. As volcanic events cannot be precisely predicted, it is valuable to have aircraft available on short notice for surveillance of deformation, infrared precursor signatures, and emissions sampling.

For Earth Surface and Interior missions, the following general requirements must be met:

- Medium altitude is suitable for many missions
- Very high altitude is desirable for magnetometry missions
- Long duration for diurnal cycles
- In situ sampling and remote sensing, ideally on the same platform
- Over-the-horizon data downlink in real-time
- Situational awareness for science team: location of aircraft at all times, along with instrument status and real-time data; coupled with weather and other conditions at flight locations; satellite tracks

Table 2.6 provides a summary of future Earth Surface and Interior missions requiring suborbital capabilities. Figure 2.5 indicates the spectrum of altitude and endurance for platforms performing these missions.

Type	Timeframe	Suborbital Program support/remarks
Satellite Cal/Val missions		
Landsat 7	Since 1999	Surface imagery / land change, Cal/Val
LDCM	2014	Surface imagery / land change, Cal/Val
New Airborne Sensor development		
UAV SAR	2007	Precision Trajectories
SIMPL, GSFC Lidar (LVIS follow-on)	2007, 8, 9	Surface change; coastal, ice mass, land subsidence
Vector helium magnetometer	2007-8	Magnetic field mapping
Airborne Process studies		
UAS SAR science	2009	Repeat pass interferometry
MASTER CONUS	2007, 8, 9	Mapping
USGS National Lidar survey	2008	Elevation mapping

Table 2.6: Summary of select future Earth surface and interior missions

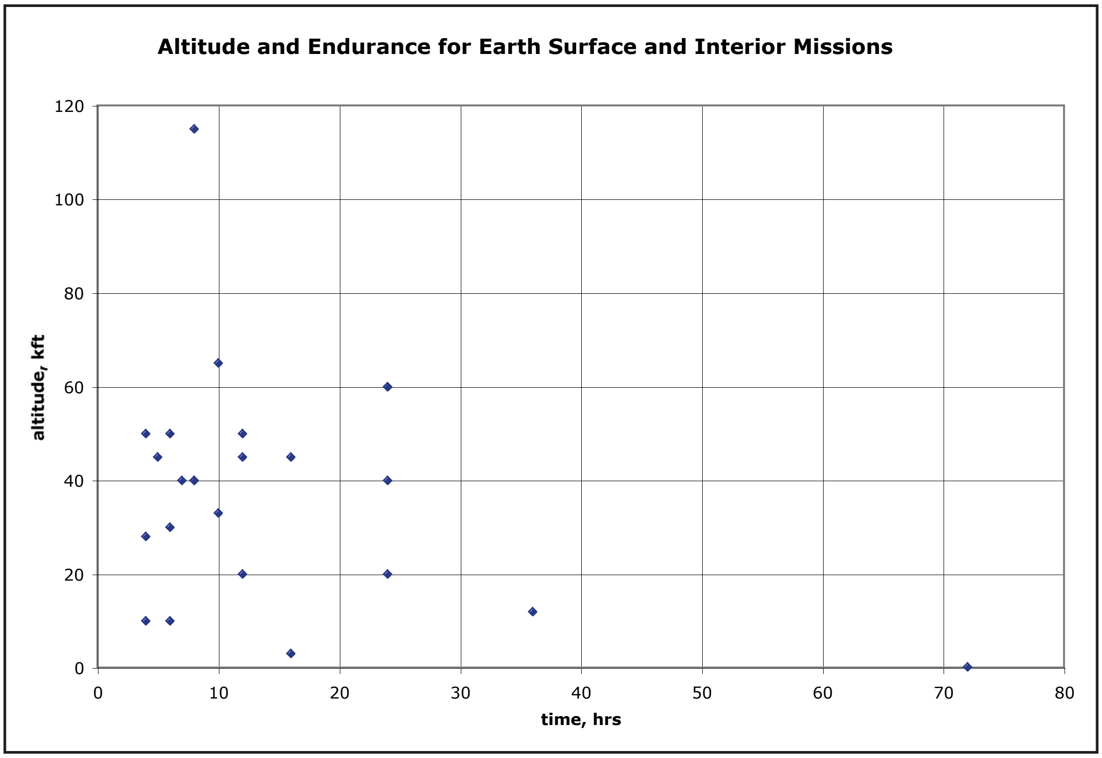


Figure 2.5: Select science measurement requirements as a function of altitude and endurance for Earth surface and interior mission goals.

2.3.5 Water and Energy Cycle

The Water and Energy Cycle Focus Area studies the distribution, transport, and transformation of water and energy within the Earth system. Since solar energy drives water and energy exchanges, the energy cycle and the water cycle are intimately entwined. Thus, research focuses on the closely linked budgets of energy and moisture.

The following questions guide research within the Water and Energy Cycle Focus Area:

- How are global precipitation, evaporation, and the cycling of water changing?
- What are the effects of clouds and surface hydrologic processes on Earth's climate?
- How are variations in local weather, precipitation and water resources related to global climate variation?
- How will water cycle dynamics change in the future?

As these water and energy cycle questions are addressed, we gain the understanding and observing capabilities to better contend with the hydrologic, water resource, and related weather issues that underlie habitability of the planet.

The overarching, long-term goal of the Water and Energy Cycle Focus Area is to develop capabilities to observe, model, and predict the water and energy cycles, including phenomena at regional scales and extreme events such as drought and floods. This goal requires an accounting of the key reservoirs and fluxes within the global water and energy cycles, including their spatial and temporal variability, through integration of all necessary observations and research tools. Further, this goal requires not only documenting and predicting trends in the rate of the Earth's water and energy cycling, but also changes in the frequency and intensity of related meteorological and hydrologic events.

Suborbital observations include measurements of water storage as soil moisture, ground water, surface water, and snow. Algorithms for future sensors that can provide better spatial and temporal resolution and coverage are developed through airborne and field experiments and a robust research and analysis program. Remote and in situ measurements are used to validate space borne measurements and model results. Future measurements will likely include high-resolution soil moisture measurements on a global scale, remote sensing of surface water in rivers and lakes, and snow water equivalent will require some new technologies to be developed, including larger apertures for both passive and active microwave instruments. Higher resolution soil moisture measurements on a global scale will also require improved downlink capabilities.

To achieve the desired accuracy in characterizing the water budget requires several key climatic inputs including sea-ice extent, as well as atmospheric water content at all levels. The energy budget requires significant inputs on solar radiation and Earth radiation.

For Water and Energy Cycle missions, the following general requirements must be met:

- Medium altitude is suitable for most missions
- Stacked or multiple aircraft for some missions
- In situ sampling and remote sensing
- Over-the-horizon data downlink in real-time
- Situational awareness for science team: location of aircraft at all times, along with instrument status and real-time data; coupled with weather and other conditions at flight locations; satellite tracks.

Table 2.7 provides a summary of future missions for the Water and Energy Cycle focus area. Figure 2.6 indicates the spectrum of platform altitude and endurance capabilities for these missions.

Type	Timeframe	Suborbital Program support/remarks
Satellite Cal/Val missions		
AQUA	Since 2002	Surface land and water imagery, Cal/Val
Cloudsat/Calipso	Since 2006	Cloud properties, precipitation, Cal/Val
Aquarius	2009	Sea salinity, Cal/Val
(Hydrous)	2009	Moisture, freeze/thaw status
New Airborne Sensor development		
Large aperture passive and active microwave instruments	2007	Soil moisture, snow water equivalent, surface water
L-band soil moisture microwave	2008	Soil moisture
RFI detector for radiometer	2007	Aquarius cal/val
Airborne Process studies		
CLPX-CO2	2007	Cold Land Processes, multi-platform
DOE-CLASIC	2007	Radiation budget, high and low altitude, soil moisture
CLPX2	2008	CLPX
HEX	2009	HEX
Stream bed mapping/river discharge	2009	Long range/endurance flights

Table 2.7: Summary of select future water and energy cycle missions

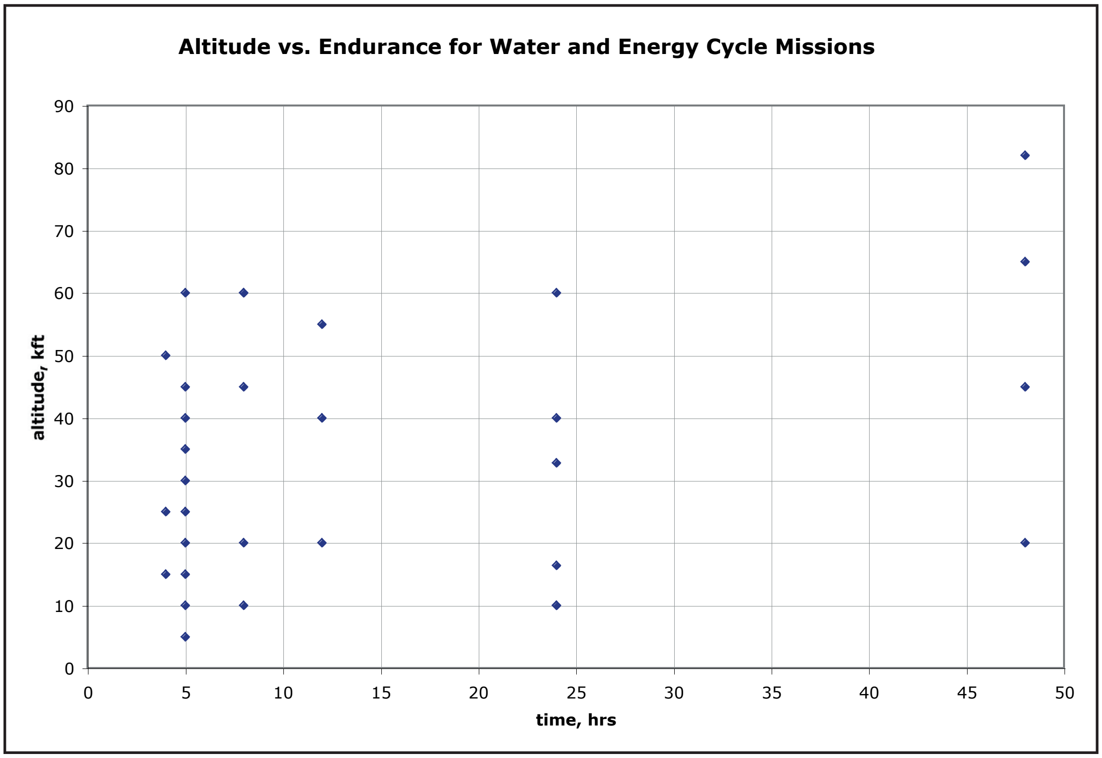


Figure 2.6: Select science requirements as a function of altitude and endurance for water and energy cycle missions.

2.3.6 Weather

The Weather Focus Area seeks to apply NASA remote sensing expertise to obtain accurate and globally-distributed measurements of the atmosphere for assimilation into operational weather forecast models thereby improving and extending weather predictions

The following direct question guides research within NASA's Weather Focus Area:

- How can weather forecast duration and reliability be improved?

Accurate local and regional predictions begin with global simulations. These simulations require the assimilation of satellite measurements of the atmosphere in depth for the entire globe. NASA develops the satellite sensors for sounding the atmosphere's temperature and humidity structure. The latest high-accuracy sensor is the AIRS instrument on board the Aqua satellite. AIRS data are being studied intensely for inclusion into operational processing streams.

Currently, high priority is assigned to the detection and quantification of rainfall rate, generally measured by microwave remote sensing. Surface radars have long been able to estimate rainfall rate, with the assumption of appropriate drop-size distributions and a national network of Doppler radars estimate the locations of wind velocity couplets that signal likely tornado formation.

In addition to precipitation measurement, important new satellite missions to advance weather forecast accuracy include an operational surface moisture monitor, geostationary monitoring of lightning location, strength, and rate, and the global monitoring of vector wind fields through out the depth of the atmosphere. Doppler lidar sensors that measure global winds as a function of height, along with measurements from advanced sounders. Such global wind sensors are being developed under the ESTO program and will need flight testing.

NASA weather research is important for the design of new satellite sensors for cloud and rainfall characteristic measurement. Focused field programs utilizing aircraft help researchers to understand the natural variability and structure of the atmosphere, clouds, and storms on finer and finer scales as the numerical models are able to handle the higher-resolution data.

For Weather missions, the following general requirements must be met:

- High altitude is required for many missions to observe from above the weather (50,000 to 60,000 ft) and provides better calibration and validation data across most of the spectrum
- Very low altitude is required for near sea-surface measurements
- Vertical profiling for some missions
- Long duration for days to weeks for cyclones; short duration for convective storms
- In situ sampling and remote sensing, although not necessarily on the same platform
- Operation in hazardous weather
- Coordination of multiple platforms in several cases
- Over-the-horizon data downlink in real-time
- Situational awareness for science team: location of aircraft at all times, along with instrument status and real-time data; coupled with weather and other conditions at flight locations; satellite tracks
- Adaptive sampling for short and long duration missions; forecast model-driven flight planning

Table 2.8 provides a summary of future weather science missions. Figure 2.7 indicates the spectrum of altitude and endurance capabilities for these missions. Note that this science area has overall need for high altitude (above weather) and a desire for the longest duration surveillance platform (two weeks).

Type	**Timeframe**	**Suborbital Program support/remarks**
Satellite Cal/Val missions		
TRMM	Since 1997	Tropical rain mapping mission, Cal/Val, medium and high altitude
Cloudsat	Since 2006	Cloud structure and precipitation, Cal/Val
NPP	2009	Cal/Val
GPM	2013	Global Precipitation Mission, Cal/Val
NPOESS	2014	Global weather, Cal/Val
New Airborne Sensor development		
HiWRAP (Heymsfeld)	2007	High altitude wind and rain profiler
TwiLiTE (Gentry)	2008	Tropospheric winds
Coherent Doppler Wind Lidar (Kavaya)	2007-8	Doppler lidar
Airborne Process studies/field campaigns		
TCSP-2	2008	Tropical cloud
PARC	2008	Pacific-Asian Regional Climate experiment
Hurricane Boundary Layer Mission, w/NOAA	2007	Low altitude, long duration
Tropical Cyclone adaptive Sampling Experiment	2008	Long-duration

Table 2.8: Summary of select future weather science missions

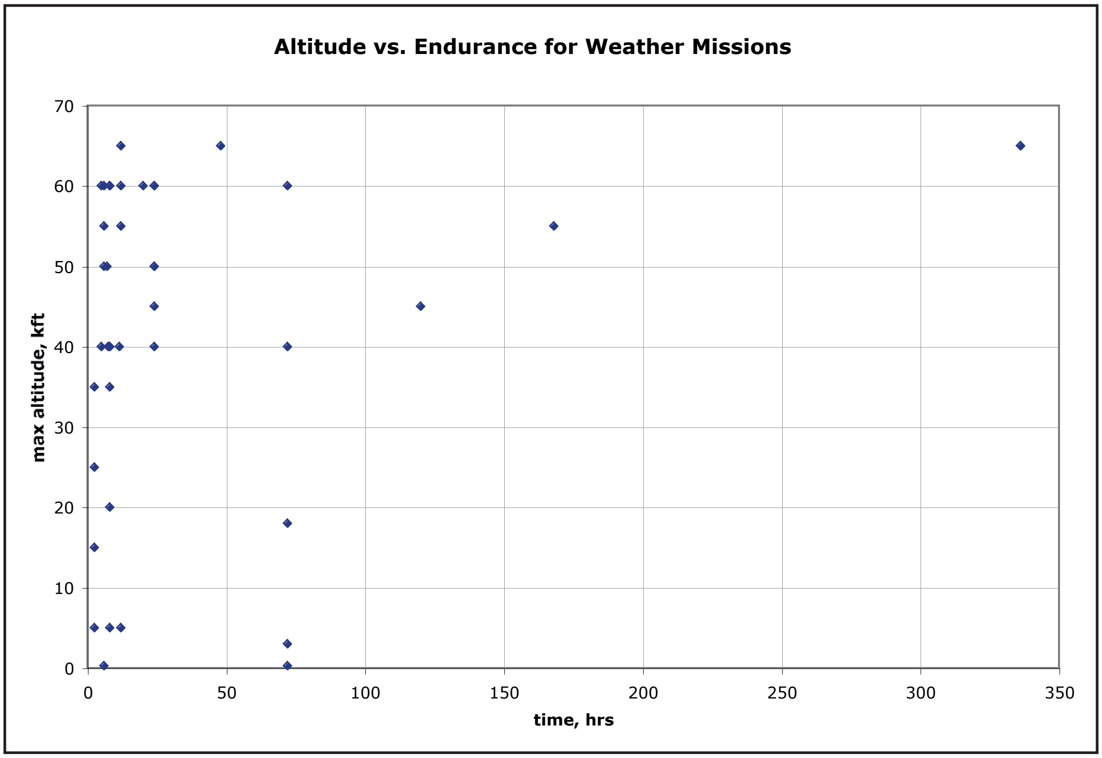


Figure 2.7: Select science requirements as a function of altitude and endurance for weather missions.

Combining the requirements for all the science focus areas together, as in Figure 2.8, shows the full spectrum of suborbital performance that is required. Beyond the wide range of altitude and endurance, a clear need is for vertical profiles.

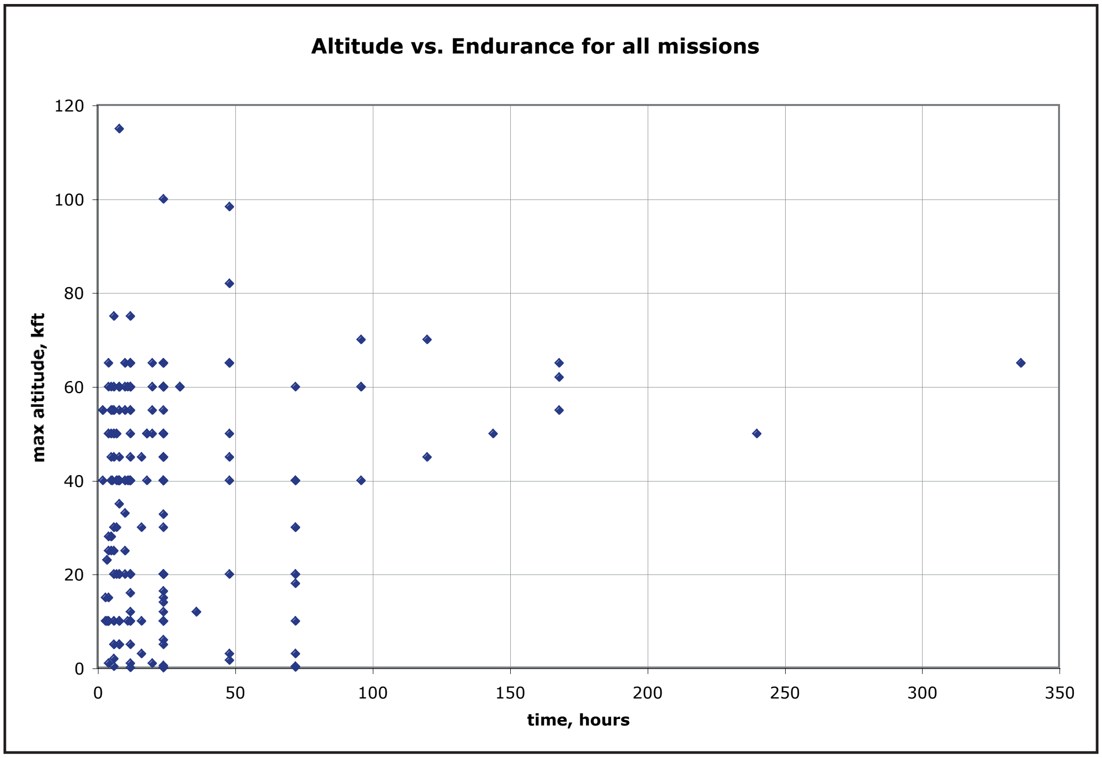


Figure 2.8: Combined science measurement requirements for future airborne science missions.

3. Suborbital capabilities needed for earth science missions.

3.1 Capabilities definitions and mission context

Long range – A long range capability allows for observations of large areas and processes that develop over great distances. Long range aircraft can be deployed out of a single location to cover large areas at reduced cost compared to aircraft deployments to remote base of operations. Longer range ultimately means more measurements and more data per mission basis. This capability is related to endurance, the distinction being that range implies a need for more powerful propulsion systems and generally larger fixed-wing aircraft. For the purpose of this analysis anything over 3000nmi is considered a long range capability.

Long endurance – Many earth system measurements are strongly influenced by the diurnal cycle such as radiation, carbon sequestration, aerosol emissions, etc. Other quickly evolving processes require near continuous high resolution observations for days or more including fires, volcanoes, algae blooms and hurricanes. A capability for long endurance entails missions of 10 hours or more.

Very high altitude – In order to simulate orbital measurements from aircraft, it is important to get as far above the atmosphere as possible in order to simulate the effect of water vapor and aerosols on orbital measurements. For this reason, instruments that do soundings of the atmosphere, or derive optical estimates of column concentrations require very high altitude platforms. Flights above 75k ft are considered very high altitude missions.

High altitude – High altitude missions, defined as flights occurring between 50k and 75k ft, provide sampling of the tropopause and lower stratosphere. These missions also enable remote sensing of measurements in conjunction with medium altitude atmospheric sampling missions. This flight regime is also important for large area imaging while still providing relatively high resolution per pixel.

Medium altitude - The flight regime from 10k - 50k ft is an important region of the atmosphere for understanding the relationship between regional chemistry of the troposphere and global chemistry of the stratosphere. Imagers are also flown in this region for high spatial resolution data approaching 1 m ground-pixel resolution. Upward and downward radiometers use this vantage point for measurements of upwelling and downwelling solar radiation, and to study the affects of aerosols on the planets radiative balance.

Low altitude – The capability to fly from 100 – 10k ft above ground level is a requirement for studies of surface exchange of heat, momentum and gases. Low altitude is also needed high resolution lidar and radar observations of land and vegetation structure. This capability is also used for boundary layer studies.

Vertical profiles – The ability to take measurements at different altitudes within the same air mass is a requisite for validating column measurements and for understanding the distribution of constituents and aerosols, and radiation attenuation through the column.

Heavy, Medium and Light Lift – Understanding the chemical composition of the atmosphere, including reaction rates, requires measuring many different species simultaneously, along with physical parameters such as temperature and pressure. Numerous different instruments are necessary to make all these measurements, which can result in a large payload. Heavy lift is defined as 4000 pounds, medium lies from 1000-4000 lbs, and light lift consists of payloads less than 1000 pounds.

Very light lift – For some very low altitude flights, especially very long endurance flights, electrically propeller (UAS) aircraft with light payloads will be most appropriate. Very light lift consists of payloads less than 25 pounds.

All weather operations – The science of severe weather sometimes calls for measurements in situ. A capability to operate in stormy conditions or at extreme temperatures is required.

Mother-daughter-ship – For some types of missions, it is important to provide column measurements in conditions where it can be difficult for manned aircraft to safely fly. An example of this type of capability would be the launch of one or more recoverable or expendable unmanned aircraft from a larger aircraft.

Terrain Avoidance – Low altitude flight for purposes of making flux measurements or topographical mapping can be very dangerous without a system that can detect sudden changes in elevation of land, canopy or wave height. This capability allows measurements in challenging locations.

Formation flight – This capability allows simultaneous measurements with spatial coverage, to determine spatial variations. Vertical (stacked formation) is required for chemical or physical variations. Horizontal formation is useful for imaging over an area.

Precision position – Knowledge of the precise location of a measurement is required for accurate mapping, both of surface and atmosphere conditions.

Precision trajectories – The capability is required to fly an exact path at different times to determine temporal variations in a given locations. One example - this allows determination of land changes.

Payload-directed flight – This capability allows real-time determination of flight path based on measurements made on-board the aircraft. Once finding a phenomenon in flight, information from the sensors can be used to direct the aircraft to provide the observations or measurements scientifically desired.

Event-driven operations (<24 hr deployment) – For unpredictable events, such as natural disasters requiring in societal observation or of significant scientific interest, it is necessary to have a capability to respond quickly. Platforms, operators, and appropriate instrumentation must be quickly and easily deployed.

Expendable systems – Some observations or measurements of interest to the scientific community are inherently risky due to the conditions in which they are made. In this case, the capability to accept loss with expendable instruments allows such measurements. The inherent quality of an expendable system is that it be inexpensive relative to the overall cost of the mission and the value of the science achieved. Hurricanes are a good example of this when dropsondes are launched from research aircraft.

Remote base of operations – This capability satisfies the need for global access to earth system processes and phenomena and directly supports the NASA ESD goal to understand the Earth as a system. Observations of the Greenland and Antarctic ice shelves or chemistry observations in the tropical tropopause are examples of missions that require this capability. Missions cannot be conducted from only U.S. territory but will need to be globally based and operated jointly with our international partners.

Over-the-horizon communications – Over the horizon command and control is required for UAS if they are to fly beyond line-of-sight. (Even if a UAS is programmed to fly autonomously, this requirement is likely to be in place for the US National Airspace for the foreseeable future.) Beyond command and control of aircraft, over the horizon telemetry allows for real-time commands to payloads (on manned or unmanned platforms) from a scientist on the ground, and real-time data from the payload to a scientist located anywhere on the ground. This capability provides efficiency and rapid response. For small data streams, low bandwidth is acceptable. For high-resolution imagery, high band-width telemetry is required. This capability will allow for more participation from the science community and allows student participation while remaining at their home institution.

Sensor portability – For efficient use of limited assets, it is important that sensor payloads be designed for use in a generic aircraft, not tied to a specific platform. The ability to fly on more than one platform greatly enhances the opportunities to fly and perform scientific missions.

3.2 Science priorities for suborbital capabilities

	Atmospheric Composition		Carbon Cycle		Climate, Cryosphere		Solid Earth		Water Cycle		Weather	
Platform Capabilities	5 year	10 year	5 year	10 year	5 year	10 year	5 year	10 year	5 year	10 year	5 year	10 year
Long Range	2; 2	1	3	2	1	0	1; 3	1; 1.5	3	2	2	1
Long Endurance	2; 2	1	3	2	1	0	1; 3	1; 1.5	3	1	2	1
Base of operations in	1; 3	1	1	1	1	0	1; 2	1; 2	1	1	2	2
Very high altitude (>60)	1; 3	1	3	2	2	0	2; 1	2; 1	3	2	1	1
Very low altitude	1;1	1	2	2	2	0	3; 3	3; 3	2	1.5	2	1
Vertical Profiling	1; 1	1	1	1	3	0	3; 3	3; 3	2	1.5	2	2
Heavy lift/Multiple	2; 1	2	1	1	1	0	3; 3	3; 3	3	2.5	2	1
All Weather	2; 2	2	3	3	1	0	1; 2	1; 2	3	2.5	1	1
Monitoring/control	3; 3	2	3	3	0	0	2; 3	1; 2	3	1.5	2	2
Terrain Avidance/	3; 3	3	2	2	1	0	3; 3	3; 3	2	1	3	3
Formation Flight/	2; 2	2	1	1	2	0	1; 2	1; 1	3	2	2	1
Precision Trajectories	3; 3	3	1	1	1	1	1; 1	1; 1	2	2	2	2
Payload-directed flight	3; 1	2	1	1	0	0	1; 1	1; 1	2	2	2	2
Quick deployment	3; 2	2	1	1	2	0	1; 1	1; 1	2	1.5	2	2
Expendable systems	3; 3	3	3	3	0	0	2; 3	2; 2	3	2	2	2

Table 3.1: Summary of select future science priorities for suborbital capabilities.
1(Red)=High Priority; 2(Yellow)=Important; 3(Grey)=Low priority; 0(white)=No data
If two numbers are in a block then two ESD Program Scientist/Mangers from that field responded
Source: NASA Earth Science Division Program Managers and Scientists survey

4. Suborbital aircraft for meeting needed capabilities

4.1 Aircraft platforms

The current fleet of SSP core aircraft, used for earth science research, has evolved based upon recurring needs for capabilities from NASA users. These unique, highly modified aircraft complement research aircraft possessed by NOAA, DOE, NRL, and DOI, by providing high altitude and heavy lift capabilities. In addition, the aircraft catalogue concept provides access to commercial vendors that can meet customer requirements.

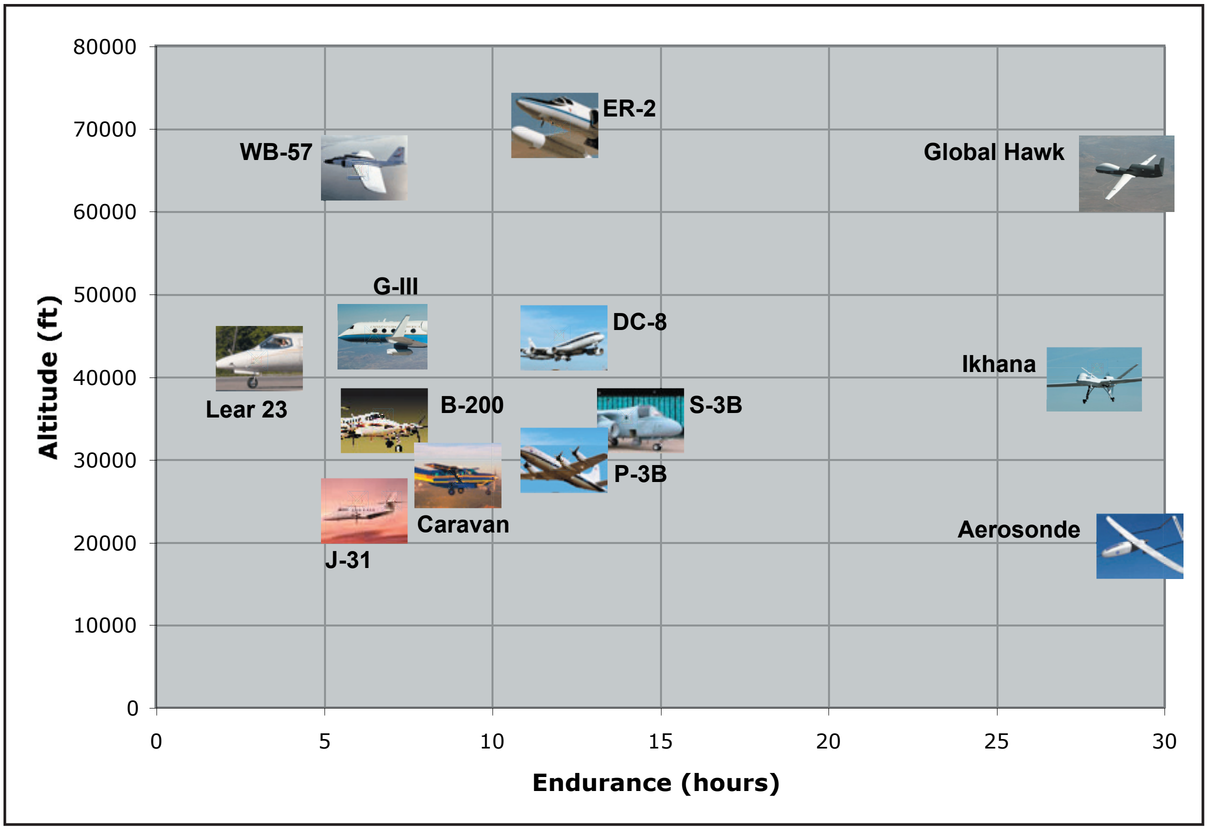


Figure 4.1: Notional aircraft capabilities for the current fleet of core, new technology, and contract catalogue aircraft being used by SSP

The NASA DC-8 Airborne Laboratory provides medium altitude, long range, heavy lift capabilities for a wide variety of experiments, collects data in support of scientific projects, and serves the world scientific community. Included in this community are NASA, federal, state, academic, and foreign investigators. This highly modified passenger jet allows for numerous PI's/operators in-flight with active, passive, and in situ sensors flying up to 45,000 ft, carrying 30,000 lbs of useful payload.

There are two WB-57 aircraft operated by NASA which are heavy lift, mid-range aircraft capable of operation for extended periods of time from sea level to altitudes well in excess of 60,000 feet, and capable of over 6000 lbs of sensors. Two crew members are positioned at separate tandem stations in the forward section of the fuselage. The pilot station contains all the essential equipment for flying the aircraft while the sensor operator station contains both navigational equipment and controls for the operation of the sensors that are located throughout the aircraft. This platform is ideal for studying the TTL with about 30 instruments simultaneously performing the needed vertical profiles between the troposphere and stratosphere.

NASA operates two high-altitude, long-range ER-2 aircraft to serve as high altitude sensor platforms to collect remote sensing and in situ data on Earth resources, atmospheric chemistry and dynamics, and oceanic processes. Operating at 70,000 feet (21.3 km) the single crewed (pilot only) ER-2 acquires data above ninety-five percent of the Earth's atmosphere. The aircraft also yields an effective line of site horizon of 300 miles (480 km) or greater at altitudes of 70,000 feet. Consequently, ER-2 sensors acquiring Earth imagery or conducting atmospheric sounding replicate spatial, spectral and atmospheric characteristics of data collected by Earth observing sensors aboard orbiting satellites.

NASA operates a Lockheed Martin P-3B for low altitude heavy lift airborne science missions. The P-3B has a long history of supporting cryosphere studies, and due to the long range of the aircraft, it is able to support ice sheet studies in both the Arctic and Antarctica polar regions. The P-3B has supported both active optical remote sensing missions and passive microwave instruments. Like the DC-8 this aircraft allows multiple PI's/operators to accompany their sensors in-flight.

These four aircraft are critical to ongoing research because of their ability to carry large payloads, accommodate human operators, make large number of measurements simultaneously, and operate in more airspace than unmanned systems. Together, the current suite of Suborbital

Platform Capabilities	**DC-8**	**WB-57**	**ER-2**	**P-3**
Long Range	X		X	X
Long Endurance			X	
Base of operations in Remote Area	X	X	X	X
Very high altitude				
High altitude		X	X	
Medium altitude	X	X		
Low Altitude	X	X		X
Low Speed				
Vertical Profiling	X	X	X	X
Heavy lift/Multiple payloads	X	X		X
All Weather Conditions	X			X
Mother-daughter-ship	X			X
Terrain Avoidance/terrain following	X	X		X
Formation Flight/stacked, horizontal	X	X	X	X
Precision Trajectories & Position/Nav data		X		X
Payload-directed flight	X	X		X
Quick deployment; event driven		X	X	
Expendable systems				

Table 4.1 Summary of NASA science aircraft and required science capabilities

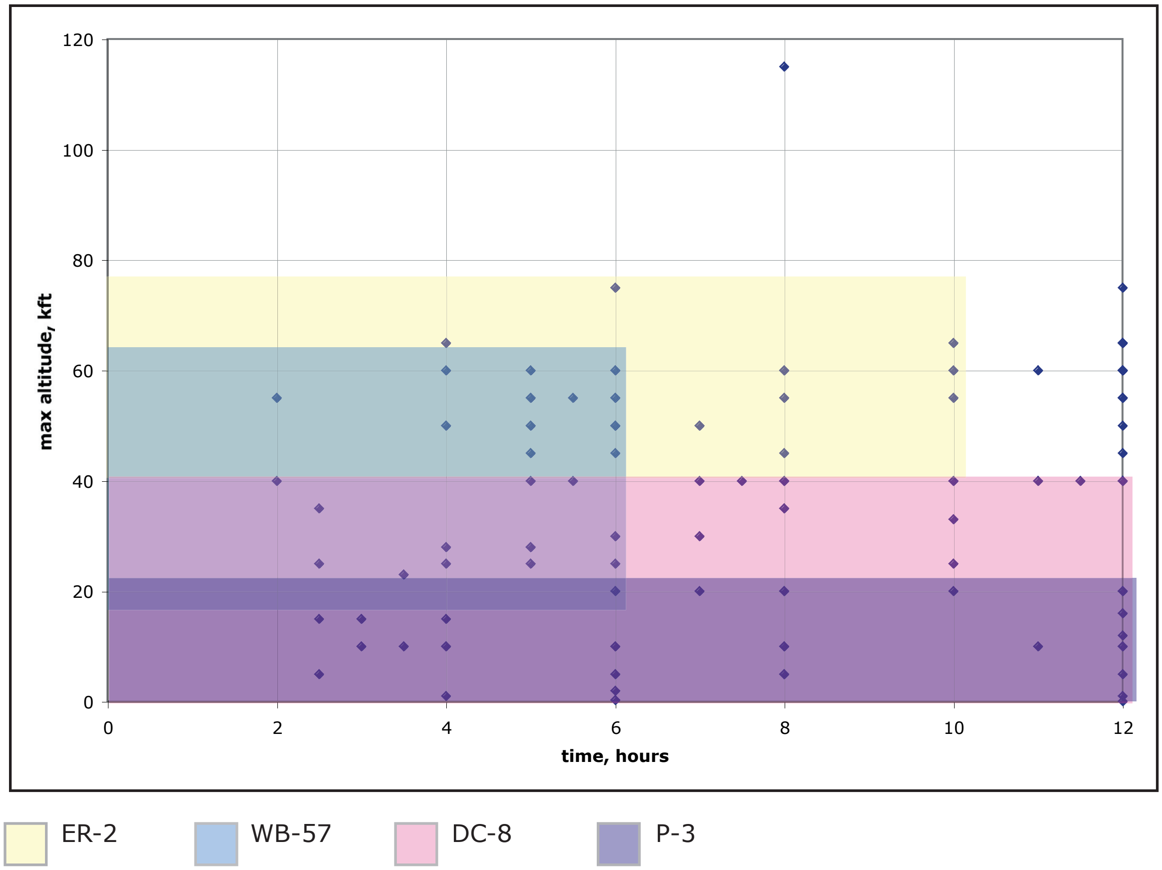


Figure 4.2: Generalized manned aircraft capabilities compared with altitude and endurance requirements for Earth Science missions of 12 hours or less in duration. All the aircraft are capable of expanding their lower altitude data collection range but these are their nominal regimes.

Science aircraft are able to perform approximately ~50% of the requirements for altitude and mission duration in future earth science mission concepts (see figure 4.1). Another 30% of the current set of expected missions can or will be achievable by new technology developments in unmanned systems. Of the remaining types of missions that the program anticipates supporting, some will be achieved through airships or advanced UAS concepts while the others will be the focus of targeted investments in new technologies and partnerships.

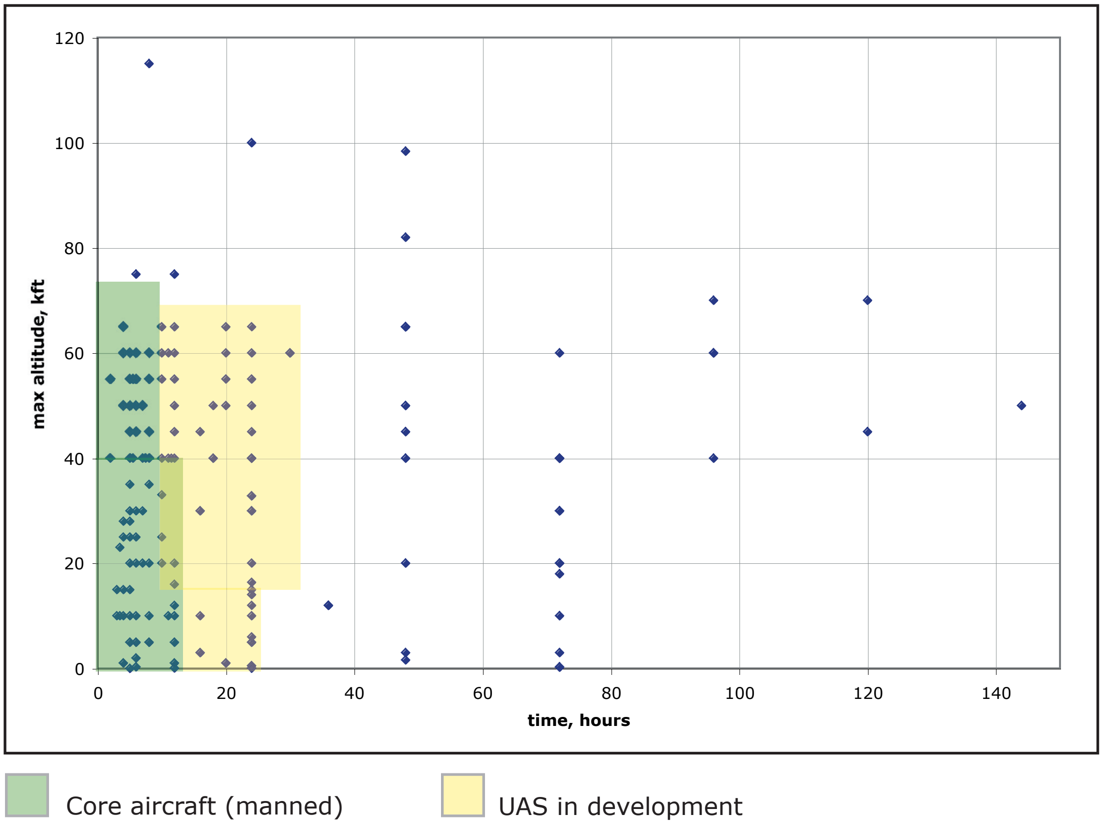


Figure 4.3: Generalized unmanned aircraft capabilities compared with altitude and endurance requirements for expected Earth Science missions over the next decade.

4.2 Aircraft subsystems and science support payloads: Payload accommodations, data handling and telemetry

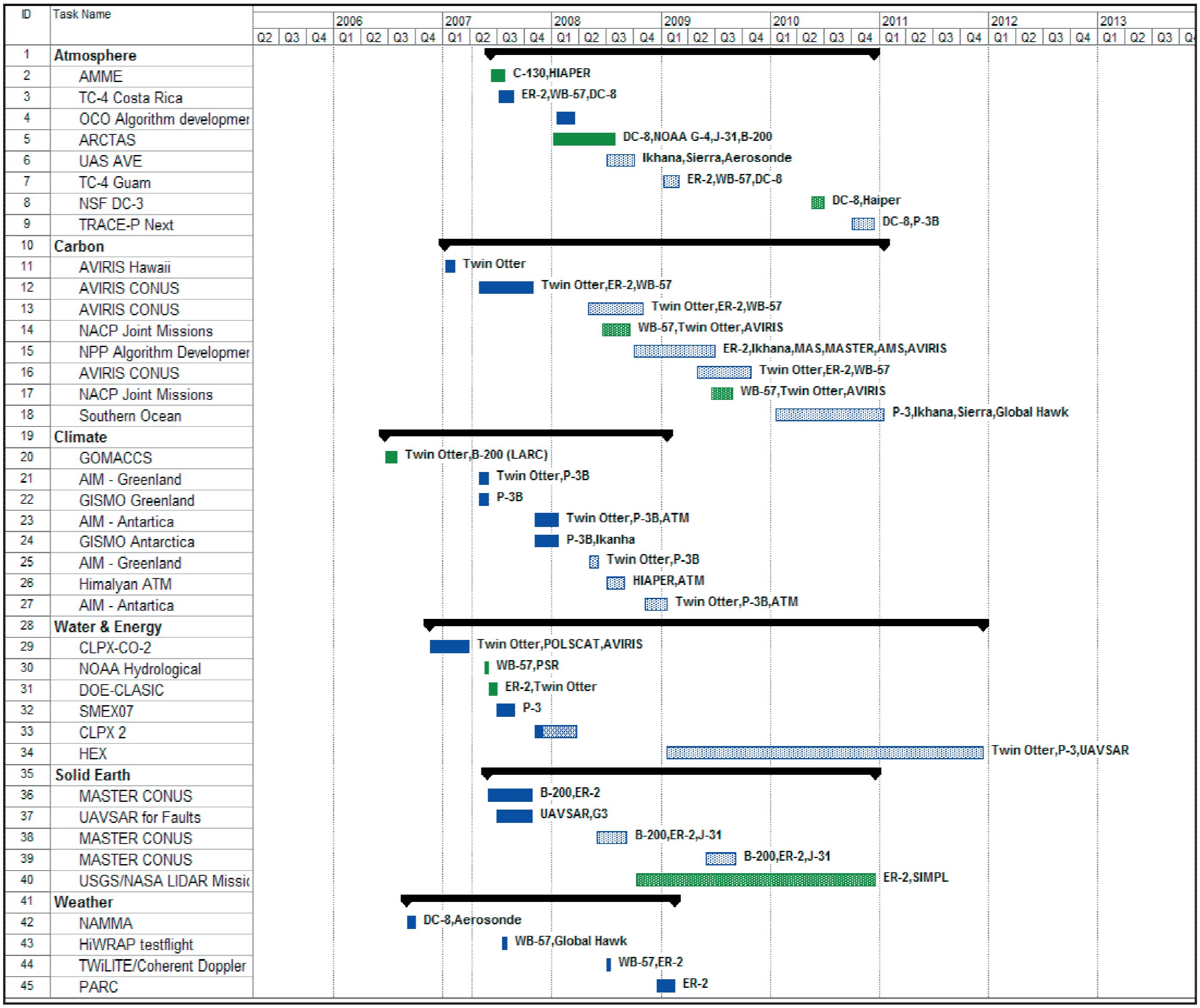
In addition to the aircraft catalog, SSP invests a small amount of program resources in science support subsystems. These systems include digital cameras for providing context images for studies, select facility sensor systems that provide data for multi-disciplinary science missions and calibration/validations studies, and navigation and flight data recorders. The New Technology element of the program is also actively pursuing solutions for providing dedicated over-the-horizon data telemetry capabilities through the REVEAL system. This system multiplexes several Iridium satellite channels to provide low bandwidth, real-time data from missions.

5. Summary

The Suborbital Science Program performs a critical role in the end-to-end process of planning and executing Earth science missions – from developing instruments and training scientists, to refining data products and ultimately enhancing models of the Earth system. The program provides airborne systems to scientists based upon the observations and measurements required to answer critical science questions. This report provides a top-level summary of the requirements for the program as they pertain to new instrument development, support for current and future satellite missions, and support for research and analysis process projects. The primary finding of this report is that the program is prepared to meet the needs of a majority of expected missions using current and planned aircraft and other assets. Nonetheless, there are still a number of specific suborbital capabilities required by NASA Earth science missions that the program cannot currently provide, including very high altitude, flights of more than 12 hours, and access to science-capable expendable systems.

This report confirms that science generates the required airborne science measurements. The report then shows how NASA's Suborbital Science Program satisfies those measurement requirements with its current and developing platform capability. Finally, the report indicates gaps in the program's capability to collect the data needed by scientists. The powerful result of this effort is the ability to now determine the platforms needed to support the science community. An area not addressed in this requirements analysis, but which is crucial to the future, is the ability to field new sensor systems and to train the next generation of principle investigators who will need them for future exploration of planet Earth.

Appendix I: 5-yr Plan of upcoming science campaigns and major missions



ID	Task Name	
1	**Atmosphere**	
2	AMME	C-130,HIAPER
3	TC-4 Costa Rica	ER-2,WB-57,DC-8
4	OCO Algorithm developmer	
5	ARCTAS	DC-8,NOAA G-4,J-31,B-200
6	UAS AVE	Ikhana,Sierra,Aerosonde
7	TC-4 Guam	ER-2,WB-57,DC-8
8	NSF DC-3	DC-8,Haiper
9	TRACE-P Next	DC-8,P-3B
10	**Carbon**	
11	AVIRIS Hawaii	Twin Otter
12	AVIRIS CONUS	Twin Otter,ER-2,WB-57
13	AVIRIS CONUS	Twin Otter,ER-2,WB-57
14	NACP Joint Missions	WB-57,Twin Otter,AVIRIS
15	NPP Algorithm Developmer	ER-2,Ikhana,MAS,MASTER,AMS,AVIRIS
16	AVIRIS CONUS	Twin Otter,ER-2,WB-57
17	NACP Joint Missions	WB-57,Twin Otter,AVIRIS
18	Southern Ocean	P-3,Ikhana,Sierra,Global Hawk
19	**Climate**	
20	GOMACCS	Twin Otter,B-200 (LARC)
21	AIM - Greenland	Twin Otter,P-3B
22	GISMO Greenland	P-3B
23	AIM - Antartica	Twin Otter,P-3B,ATM
24	GISMO Antarctica	P-3B,Ikanha
25	AIM - Greenland	Twin Otter,P-3B
26	Himalyan ATM	HIAPER,ATM
27	AIM - Antartica	Twin Otter,P-3B,ATM
28	**Water & Energy**	
29	CLPX-CO-2	Twin Otter,POLSCAT,AVIRIS
30	NOAA Hydrological	WB-57,PSR
31	DOE-CLASIC	ER-2,Twin Otter
32	SMEX07	P-3
33	CLPX 2	
34	HEX	Twin Otter,P-3,UAVSAR
35	**Solid Earth**	
36	MASTER CONUS	B-200,ER-2
37	UAVSAR for Faults	UAVSAR,G3
38	MASTER CONUS	B-200,ER-2,J-31
39	MASTER CONUS	B-200,ER-2,J-31
40	USGS/NASA LIDAR Missic	ER-2,SIMPL
41	**Weather**	
42	NAMMA	DC-8,Aerosonde
43	HiWRAP testflight	WB-57,Global Hawk
44	TWiLITE/Coherent Doppler	WB-57,ER-2
45	PARC	ER-2

Appendix II: 5-yr Plan of upcoming satellite missions