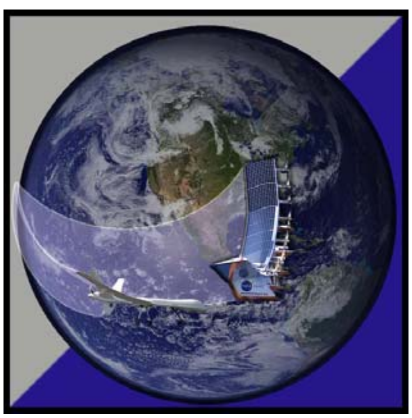
Earth Observations and the Role of UAVs:

Volume 2
Appendices

Version 1.1

Prepared For: Cheryl Yuhas
Suborbital Science Program Manager
NASA Science Mission Directorate

Prepared By: Civil UAV Assessment Team
http://www.nasa.gov/centers/dryden/research/civuav/index.html



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Civil UAV Assessment Team Authors

Principal Authors:
Timothy H. Cox – NASA DFRC
Ivan Somers, PhD – Bandwidth Solutions, Inc.
David J. Fratello – Zel Technologies LLC

Contributing Authors:
Christopher J. Nagy – NASA DFRC
Susan Schoenung, PhD – Longitude 122 West, Inc.
Robert J. Shaw, PhD – NASA Glenn
Mark Skoog – NASA DFRC
Ryan Warner – NASA DFRC

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Introduction

This volume of the Assessment contains the Appendices that support the content and observations found in Volume 1. Because of the size of the document in number of pages, it has been divided for the sake of convenience. It is noted that Appendix A (Acronyms, Abbreviations and Definitions) and Appendix F (GOTChA Chart) are contained also in Volume 1 for the convenience of the reader since many references to these Appendices are made in the text of Volume 1. The bibliographic portion of Appendix I (References and Information Sources) appears in Volume 1 for the same reason.

Appendix B provides the reader with examples of projects that are focused on UAVs from both operational and developmental aspects. It should be noted that some of these projects are no longer operating or in existence. Many have achieved the expected project goals and others have been overtaken by better technologies or have been terminated because of budgetary constraints and marginal expected technology gains. However, substantial technological gains have been accomplished through these projects. Building on these gains will enhance the capabilities of future UAV efforts as well as on-going UAV projects.

Appendix A

Acronyms, Abbreviations and Definitions

3D	Three Dimensional
AGL	Above Ground Level
ASA	Aerospace States Association www.aerostates.org
ASC/RA	Aeronautical Systems Center / Reconnaissance Aircraft
AFRL	Air Force Research Laboratory
AuRA	Autonomous Robust Avionics – A NASA project intended to enable aircraft to fly with reduced or no human intervention, to optimize flight over multiple regimes, and to provide maintenance on demand towards the goal of a feeling, seeing, sensing, sentient air vehicle. http://avst.larc.nasa.gov/projects_aura.html
BORTAC	Border Patrol Tactical Team
CAMEX	Convection and Moisture Experiment
cm	centimeter
C	a frequency sub-band
C^2	Command and Control
C^3I	Command, Control, Communications and Intelligence
CDOM	Color Dissolved Organic Matter
Cnty.	County
CIRPAS	Center for Inter-Disciplinary Remotely Piloted Aircraft Studies (see Appendix B)
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
COA	Certificate of Authorization
DARPA	Defense Advanced Research Projects Agency
Dept.	Department
dGPS	Differential Global Positioning System
DHS	Department of Homeland Security
Dir.	Directorate
DoD	Department of Defense
DOE	Department of Energy

DOI	Department of the Interior
Ec	Expectation of Casualty
Emer.	Emergency
EO	Electro-Optical
EOS	Earth Observing System – EOS is composed of a series of satellites, a science component, and a data system supporting a coordinated series of polar-orbiting and low inclination satellites for long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans. http://eospso.gsfc.nasa.gov/
EPA	Environmental Protection Agency
ESCD	Earth Sciences Capability Demonstration
FAA	Federal Aviation Administration
FedEx	Federal Express
FEMA	Federal Emergency Management Agency
ft	feet
FTIR	Fourier Transform Infrared – An analytical technique used to identify organic and inorganic materials which measure the absorption of various infrared light wavelengths by the material of interest. These infrared absorption bands identify specific molecular components and structures. http://www.mee-inc.com/ftir.html
FY	Fiscal Year
GHz	Giga-Hertz
GIFTS	Geostationary Imaging Fourier Transform Spectrometer – This satellite uses an Imaging Fourier Transform Spectrometer to observe atmospheric temperature, water vapor content and distribution, and the concentration of certain other atmospheric gases present at a given altitude over time. http://oea.larc.nasa.gov/PAIS/GIFTS.html
GOTChA	Goals, Objectives Technical Challenges and Approaches
GPM	Global Precipitation Measurement – This science mission has the goals of improving the accuracy of climate predictions, providing more frequent and complete sampling of the Earth's precipitation, and increase the accuracy of weather and precipitation forecasts. http://gpm.gsfc.nasa.gov/index.html
GPS	Global Positioning System
Grp.	Group
HAB	Harmful Algal Blooms
HALE	High Altitude Long Endurance
hr	hour
Hz	Hertz
ITAR	International Traffic in Arms Regulations
ICE	Immigration and Customs Enforcement

IMU	Inertial Measurement Unit
IMM	Intelligent Mission Management
IMU	Inertial Measurement Unit
iNet	Integrated Network Enhanced Telemetry
INS	Inertial Navigation System
INST	Institute
IR	Infrared
ISR	Intelligence, Surveillance, and Reconnaissance
J-UCAS	Joint Unmanned Combat Air System
K	a frequency sub-band
Ka	a frequency sub-band
Ku	a frequency sub-band
kg	kilograms
km	kilometer
kW	kilowatt
L	a frequency sub-band
lbs	pounds
LIDAR	Light Detection And Ranging – This instrument transmits light which interacts with and is changed by a target. Some of this light is reflected / scattered back to the instrument where it is analyzed. It can be used to measure distance, speed, rotation, or chemical composition and concentration. http://www.ghcc.msfc.nasa.gov/sparcle/sparcle_tutorial.html
LOS	line of sight
m	meter
mm	millimeter
M	Million
MALE	Medium Altitude Long Endurance
MAV	Mini Aerial Vehicle
Mbps	Mega-bits per second
MODIS	Moderate Resolution Imaging Spectroradiometer - This instrument aboard the Terra and Aqua satellites is used for acquiring data about the global dynamics and processes occurring on the land, in the oceans, and in the lower atmosphere. http://modis.gsfc.nasa.gov/about/index.html
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
Natl	National
NCEP	National Centers for Environmental Prediction – This organization

	delivers national and global weather, water, climate and space weather guidance, forecasts, warnings and analyses to its partners and external user communities. http://wwwt.ncep.noaa.gov/mission/
NGA	National Geospatial-Intelligence Agency – This organization provides geospatial intelligence, which includes but is not limited to imagery, maps, charts, and environmental data, in support of national security. http://www.nga.mil
NO_2	Nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration
N_2O	Nitrous oxide
NOx	Nitrogen oxides
nm	nautical miles
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NFS	National Forest Service
NSF	National Science Foundation
O_2	Oxygen
OTH	Over-The-Horizon
P	a frequency sub-band
PAGNC	Precision Absolute Guidance, Navigation, and Control
pH	Potential of Hydrogen, a measure of acidity
PRGNC	Precision Relative Guidance, Navigation, and Control
PSC	Polar Stratospheric Clouds
PV	Photovoltaic
R&D	Research and Development
RF	Radio Frequency
ROA	Remotely Operated Aircraft
RTCA	Radio Technical Commission for Aviation
SAR	Synthetic Aperture Radar
SATCOM	satellite communication
sec	Second
Serv.	Services
SIGINT	Signals Intelligence
SO_2	Sulfur dioxide
SST	Sea Surface Temperature
STOL	Short take-off and landing
TBD	To Be Determined
Tech	Technology

TF	Technology Forecasting
THORPEX	The Observing-system Research and Predictability Experiment – THORPEX is an international research and development program to accelerate improvements in the accuracy high impact weather forecasts. http://www.wmo.int/thorpex/mission.html
TRL	Technology Readiness Level
UAV	Uninhabited or Unmanned Aerial Vehicle
TUAV	Tactical Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
UPS	United Parcel Service
U. S.	United States
US	United States
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VTUAV	Vertical Takeoff Unmanned Aerial Vehicle
VHF	Very High Frequency
VIIRS	Visible Infrared Imager Radiometer Suite – The group of instruments collects visible/infrared imagery and radiometric data, which includes atmospheric, clouds, Earth radiation budget, clear-air land/water surfaces, sea surface temperature, ocean color, and low light visible imagery. http://www.ipo.noaa.gov/Technology/viirs_summary.html
VTOL	vertical take-off and landing
W	Watts

Appendix B

UAV Programs

B.1 Historical Perspective

Section 2.1 of the Assessment Document gives a brief overview of the history of UAVs. It is not intended to be an exhaustive treatment of the subject matter, but rather a summary to give relevance to this document. Not all of the projects listed here are currently on-going. These have been included because of the contributions to the body of knowledge supporting technologies relevant to UAVs.

B.2 UAV Development in the U.S.

A recent study by Forecast International of the worldwide UAV market concluded that U.S. spending on UAVs amounted to about 73% of worldwide research and production spending in 2003. The U.S. has dominated this market in recent years due, in part, to the depth of research and wide range of production programs. However, UAV development has been spotty, with clear leadership in endurance UAVs but laggard performance in fielding tactical UAVs, especially compared with Europe. The RQ-4A Global Hawk reached the serial production stage in 2003. Despite the "newness" of the system, it has become synonymous with high-endurance UAVs. A single Global Hawk was employed in Operation Iraqi Freedom, but was credited with providing intelligence that led to destruction of 13 air defense missile batteries, 50 surface-to-air missile launchers and 300 tanks. Because of its reliability, Global Hawk was the first UAV to be granted an overarching Certificate of Authorization (COA) by the FAA to fly in U.S. air space system. This allows Global Hawk to significantly reduce the time notification to the FAA when a flight is required. This is a critical hurdle, not only for Global Hawk but for UAVs in general, particularly if they are to break into the civilian market.

The dominant U.S. manufacturers include:

- Lockheed Martin
- Aurora Flight Sciences
- General Atomics
- Northrop Grumman
- AeroVironment

B.3 European and Worldwide UAVs

Europe currently represents the second-largest UAV market. While quite a bit of research has been funded in Europe over the past decade, procurement has been modest and mostly confined to small numbers of tactical UAV systems. For example, France acquired less than two dozen Crecerelle UAVs and Britain's Phoenix tactical UAV program involved only about 100 air vehicles. More ambitious programs are underway, with most of the major armed forces acquiring more modern tactical UAV systems and beginning to acquire endurance systems comparable to the U.S. Air Force Predator. A recent study concluded that Europe will nearly double its share of the world UAV market in 10 years, to about 19% from about 11% of the market due to these many new programs. Britain has a comprehensive program under its Watchkeeper program, with two teams now competing for an eventual procurement phase. France is planning to acquire an upgraded version of the Crecerelle/Sperwer for its tactical UAV requirement, and is also acquiring a version of the Israeli Heron as part of its Eagle endurance UAV program. France is also sponsoring a broad range of other UAV systems from micro- and mini-UAVs through to other novel applications such as naval UAVs. Germany is finally acquiring the Tucan tactical UAV, a derivative of the long-delayed, multinational Brevel program in which France was once a partner. The German army has been a particularly active supporter of mini-UAVs, with the Luna already in service, and several other programs underway. In the endurance field, Germany is also studying the Global Hawk for maritime surveillance under its Eurohawk program. Italy has significantly expanded its UAV efforts, prompted in no small measure by turmoil in the neighboring Balkans in the 1990s. Having already procured Predators for the endurance role, it is finally funding a long-delayed tactical UAV system for the army and beginning to examine other requirements. Sweden has a broad research effort on UAVs, though so far Swedish procurement has been fairly limited. Many of the smaller European armed forces have already fielded a new-generation tactical UAV system, though often in small numbers. The most popular system has proven to be the Sagem Sperwer.

In terms of developments in the civil arena, Pegasus, a high altitude, long endurance platform, is being developed by the Flemish Institute for Technology Research for remote sensing applications. The concept is launched from a balloon at its operating altitude, where solar based engines power the vehicle for several months.

Non-European countries also have a significant UAV role. Israel, which was the pioneer for many of the current tactical UAV efforts, has continued to be a major player in UAV sales to smaller armed forces around the globe. Israel continues to innovate in the UAV field. One of its more intriguing programs is an effort to contract out UAV services. Aeronautics Unmanned Systems has been employing its Aerostar tactical UAV to conduct surveillance missions for the Israeli Defense Forces under a government contract rather than directly selling the systems. One of Israel's most important UAV sales in recent years was to India, as part of a broader effort to involve the latter in joint military technology ties. India is interested in a robust reconnaissance capability in the difficult terrain of Kashmir, and decided to buy some off-the-shelf Israeli UAVs rather than wait for its indigenous programs to mature. Pakistan is employing indigenous UAVs as well as imported Chinese UAVs along the troubled frontier with India. In the Pacific, Japan has an active UAV program, but long-term goals remain sketchy. Japan is planning to develop an analog to Global Hawk. Australia has shown special interest in endurance UAVs due to the sheer scale of its zone of strategic interest. With conditions in Indonesia remaining so unsettled, Australia is considering the Global Hawk as a means to monitor trouble spots along its northern maritime frontier. Australia has already deployed small numbers of UAVs for surveillance and patrol on several of its peace-keeping missions in the southwestern Pacific. China has displayed a variety of

UAVs at international trade shows; though there is little evidence to what extent such systems have been deployed in its army.

Non-U.S. UAV manufacturers include:

- Elbit
- Israeli Aircraft Industries, Inc.
- Sagem SA
- European Aeronautic Defense and Space Company
- Dassault Aviation

B.4 Civil UAVs

The following sections describe the characteristics of some of the more prominent UAVs applicable to civilian (defined as non-DoD) missions. The aircraft listed here, chosen primarily for previous roles in science missions, serves as a sampling of civil UAV systems and is not intended to be complete and exhaustive. A more complete listing of UAVs may be found in the following reference: *Aviation Week and Space Technology, "2005 Aerospace Source Book", January 17, 2005*.

B.4.1 Operational Civil UAVs

The following sections discuss a few of the civilian UAV that are considered to be operational.

B.4.1.1 Aerosonde

The Aerosonde UAV was developed by Aerosonde Pty, Ltd. of Australia. It was originally designed for meteorological reconnaissance and environmental monitoring although it has found additional missions. It has a gross take-off weight of 33 lbs (15 kg) and a payload weight ranging from 4.5 to 11 lb (2 to 5 kg) depending on the desired endurance. For intermediate weights, the Aerosonde has a ceiling of 23,000 ft (7 km). It has an endurance of 10 to 30 hours and a range of 1100 to 1600 nm (2000 to 3000 km), depending on the payload weight. Aerosondes are currently being operated by NASA Goddard Space Flight Center for Earth science missions.

B.4.1.2 Altair

Altair was built by General Atomics Aeronautical Systems Incorporated as a high altitude version of the Predator B aircraft.

Designed for increased reliability, it has a fault-tolerant flight control system and triplex avionics. It is capable of payloads of 660 lbs (300 kg) internally and up to 3000 lbs (1361 kg) on external wing stations. Altair has a ceiling of 52,000 feet (15.2 km) and an endurance of 30 hours. It is operated by General Atomics although NASA Dryden Flight Research Center maintains an arrangement to conduct Altair flights.

B.4.1.3 Altus I / Altus II

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC98-44684-1 Date: 29 Jun 1998 Photo by: General Atomics

Altus II aircraft flying over southern California desert

The Altus aircraft were developed by General Atomics Aeronautical Systems Incorporated, San Diego, CA, as a civil variant of the U.S. Air Force Predator. Although similar in appearance, the ALTUS has a slightly longer wingspan and is designed to carry atmospheric sampling and other instruments for civilian scientific research missions in place of the military reconnaissance equipment carried by the Predators. It can carry up to 330 lbs of sensors and other scientific instruments in a nose-mounted payload compartment, a location designed to allow air being sampled by the sensors to be undisturbed by heat or pollutants from engine exhaust. Altus II has a ceiling of about 65,000 ft (19.8 km) and an endurance of about 24 hours.

General Atomics (now GA-Aeronautical Systems, Inc.) built the first Altus with a single-stage turbocharger that was modified subsequently to a two-stage turbocharger and renamed the "Altus II". This aircraft currently resides at NASA Dryden Flight Research Center. The second single-stage Altus was built for the DOE ARM-UAV Program (see Section B 4.2 on CIRPAS), in 1996. ARM-UAV bought the Altus I and a ground control station. These were subsequently given by ARM-UAV to the Navy under a joint-use agreement.

B.4.1.4 RMAX

The Yamaha RMAX helicopter has been around since about 1983. It has been used for both surveillance and crop dusting, as well as other agricultural purposes. It has a payload of about 65 lbs (30 kg), a flight time of about 90 minutes, and range of about 5.5 nm (10 km).

B.4.2 Center for Interdisciplinary Remotely-Piloted Aircraft Studies

The Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) is a research center at the Naval Postgraduate School. The Office of Naval Research established CIRPAS in the spring of 1996. CIRPAS provides measurements from an array of airborne and ground-based meteorological, aerosol and cloud particle sensors, radiation, and remote sensors to the scientific community. The data are reduced at the facility and provided to the user groups as coherent data sets. The measurements are supported by a ground-based calibration facility. CIRPAS conducts payload integration, reviews flight safety and provides logistical planning and support as a part of its research and test projects around the world. The Center operates a variety of manned aircraft and unmanned aerial vehicles. Its aircraft include the UV-18A 'Twin Otter', the Pelican, the Altus ST UAV, the Predator UAV, and the GNAT-750 UAV. CIRPAS is also a National Research Facility of the University National Oceanographic Laboratory System.

The facility provides unique flight operation and scientific measurement services by:

- Providing access to manned aircraft, UAVs and support equipment, as well as to scientific instruments, to spare users the cost of ownership, guaranteeing equal access by all interested parties on a first-come, first-served basis.
- Instrumenting and operating aircraft to meet the requirements of a variety of individual research and test programs.
- Developing new instrumentation to meet increasing challenges for improvements in meteorological and oceanographic measurements.
- Calibrating, maintaining, and operating the facility's airborne instruments in accordance with individual mission specifications.
- Integrating auxiliary payloads as required and handling flight safety and logistics tasks, allowing the user to concentrate on his specific mission goals.

B.4.3 UAV Technology Development Programs

NASA is currently leading a series of efforts that will impact the capabilities of future UAVs. A brief review of these programs is presented here.

- **Earth Sciences Capability Demonstration (ESCD)**

Sponsored jointly by the Science and Aeronautics Research Mission Directorates, ESCD is oriented toward developing component systems to make UAVs more functional for science missions.

- **High Altitude Long Endurance Remotely Operated Aircraft (HALE ROA)**

HALE ROA aircraft goals were to redefine duration and payload capabilities of high altitude UAVs. Flight demonstrations were planned to have duration goals of weeks-to-months. Although this project is not active currently, the discussion is important to understand this class of UAV for certain missions described elsewhere in this Assessment.

One key to the success of this project is developing and maturing the technology which will enable aircraft to fly with reduced or no human intervention, to optimize flight over multiple regimes, and to provide maintenance on demand. Main components of the HALE program, formerly covered under the Autonomous Robust Avionics (AuRA) program, are Intelligent Mission Management (IMM), Integrated Systems Vehicle Management (IVSM), and adaptive flight controls.

One characteristic of HALE-type vehicles is large, high aspect ratio wings which require significant structural flexibility. Improvement in the structural capabilities of these type vehicles is another key technology development addressed by the program.

Development of non-conventional propulsion technology is required to enable HALE vehicles. Technical focus areas directed towards HALE ROA applications include hydrogen/oxygen regenerative fuel cell system, materials for high temperature PEM fuel cells, solid oxide fuel cells, and lightweight hydrogen-based storage and feed systems.

- **Remotely Operated Aircraft in the National Airspace (ROA in the NAS)**

NASA centers, the Federal Aviation Administration (FAA) and other governmental agencies have united in an effort to develop recommendations to the FAA for certifications and procedures to incorporate UAVs into the national airspace. The assignment is to alleviate a key impediment to development of the commercial UAV market. Currently the program is funded for two phases. The first phase will consist of recommendations for flight above 40,000 feet. The second phase will consist of recommendations for flight above 18,000 feet. Originally part of Access-5 project, other entities have assumed this effort, namely, RTCA.

B.4.4 Military UAVs

The DoD recognizes that UAV technology has the potential to transform the way in which warfighting is conducted. In recent military operations, operational UAVs such as Predator, Hunter, and Shadow, and developmental UAVs such as Global Hawk have demonstrated a significant force-multiplier capability. As such, the DoD is expanding the role of the UAV within military concepts of operation. Due to the large variety of military UAVs, a brief summary of the classes of UAVs in current operation or development follows, as well as a description of some current military technology development programs which will provide the capability for operational concepts using UAVs over the next 20 years. More specific information can be found in the DoD UAV roadmap (*Unmanned Aerial Vehicles Roadmap, Office of the Secretary of Defense, December 2002*). A general history of military UAV development is shown in Figure 2.1.

a) Classes of Military UAVs

For the purposes of this report, UAVs are classified into 4 categories: micro aerial vehicles, local area support vehicles, tactical area support vehicles, and theatre area support vehicles.

Micro aerial vehicles are defined by their physical dimensions. They are no larger than 12 inches (.3 m) in any direction. Total weights of these vehicles range from .2 lbs (.1 kg) to a few pounds with payload weights on the order of fractions of pounds. They are easily transported and operated by one individual, through both autopilot and remotely piloted modes. The primary use is for reconnaissance support of the individual soldier or squad of soldiers. The payload is a miniaturized camera. Examples of these vehicles include the Black Widow, the 9” (.23 m) ducted fan iSTAR (intelligent Surveillance, Target acquisition, and Reconnaissance), and the Wasp.

Vehicle: Wasp
Manufacturer: AeroVironment
Weight: .4 lbs (.18 kg)
Payload weight: .01 lbs (.004 kg)
Length: 8 inches (.20 m)
Max speed: 35 knots (65 km/hr)
Endurance: 100 minutes

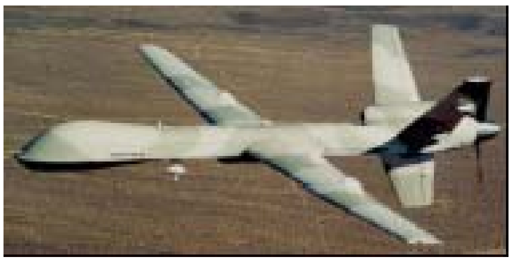
Local area support vehicles are designed to be carried in a backpack or on a ground transport vehicle to support squad or platoon level operations. They are operated by one or two individuals, generally through the use of waypoint guidance or autopilot interface and remotely piloted mode. Total weight for these vehicles can range from 5 to 50 pounds (2.3 to 23 kg), with payload weights from 1 to 5 pounds (.45 to 2.3 kg). Typical payloads are a suite of electro-optical (EO) cameras; sometimes infrared (IR) cameras are included. The mission is 'over-the-hill' type reconnaissance. Examples of these vehicles include the 29" (.74 m) ducted fan iSTAR, Pointer, Dragon Eye, and Raven.

Vehicle: Pointer
Manufacturer: AeroVironment
Weight: 8.3 lbs (3.7 kg)
Payload weight: 2 lbs (.9 kg)
Length: 6 ft (1.8 m)
Max speed: 43 knot (80 km/hr)
Endurance: 120 minutes

Tactical area support vehicles are operated by a crew in support of brigade, battalion, division, or corps level commanders. Total weights for these vehicles range from 300 lbs (136 kg) to about 2000 or 3000 lbs (907 or 1360 kg). Conventional take-off from a runway or catapult-assisted launches are necessary for fixed wing aircraft. Rotary wing vehicles are also being developed in this class. The primary role of these vehicles is reconnaissance with increased ranges over previous classes, anywhere from 50 to 150 nm (92.5 to 278 km). Examples of these vehicles include Shadow, Hunter, and Dragon Warrior.

Vehicle: Hunter
Manufacturer: Northrop Grumman
Weight: 1600 lbs (725 kg)
Payload weight: 200 lbs (91 kg)
Length: 23 ft (7 m)
Endurance: 11.6 hr
Radius of Operation: 144 nm (266 km)

Theater area vehicles provide support for theater level commanders. Total weights for these fighter aircraft size vehicles range from 2000 to 35000 pounds (907 to 15,900 kg). Support includes tactical and strategic reconnaissance and, recently, strike capability. These vehicles operate from an airport or carrier. Some vehicles in the class are flown remotely piloted, and some with a high level of autonomy. One distinguishing feature of the current inventory within this class of vehicle is endurances beyond 24 hours. Payloads include EO/IR cameras, synthetic aperture radar (SAR), and in the case of the Predator and Predator B aircraft, Hellfire air to ground missiles. Besides the two Predator aircraft, another example of an aircraft in this class is the Global Hawk. Although still in a relatively early stage of development, Joint Unmanned Combat Air System (J-UCAS) is a vehicle in this class which will provide an air defense suppression capability.



Vehicle: Predator B
Manufacturer: General Atomics
Weight: 10,000 lbs (4536 kg)
Internal payload weight: 750 lbs (340 kg)
External payload weight: 3000 lbs (1360 kg)
Endurance: 30+ hr
Radius of Operation: 2500 nm (4625 km)

b) UAV Technology Development Programs

DARPA and all branches of the military are currently engaged in several technology development programs to enhance the capability of UAVs as a war-fighting machine. A brief summary of a few of these programs provides a taste of how UAVs are intended to be used in the future and the types of technologies required to fulfill their roles.

B.4.4.1 J-UCAS

The initial operational role of the J-UCAS program is to develop an air defense suppression system which integrates seamlessly with a ‘first day of the war’ strike package. Key technical challenges include interoperability with other manned and unmanned assets, highly adaptive autonomous operations, coordinated multi-vehicle flight and robust prognostics and health management systems. Affordability and reduced costs are an important consideration. As a result the system is to be designed with a significant reduction in the manpower required to operate and maintain vehicles.

The concept calls for the J-UCAS system to be a ‘system of systems’. Therefore the J-UCAS system is not one vehicle, but a team of vehicles coordinating and working together to perform the mission, managed by one operator. The J-UCAS concept will advance UAV technology considerably. The UAVs that are members of the J-UCAS system require a higher level of autonomy than previously flown. Potentially, nominal human involvement is to occur for approval of the J-UCAS system to launch missiles only. Therefore, mission planning must occur at a high level of autonomy. Dynamic mission re-planning, including contingency management, must be capable ‘on the fly’ within each UAV in the system, as well as within the J-UCAS system as a whole. Each UAV member within the system must be able to communicate with other members for the purpose of identifying targets, verifying targets, planning an attack, executing the attack, and performing battle damage assessment. The J-UCAS system must also be capable of determining when to return to base, and then integrating with other manned and unmanned assets for terminal area operations such as approach and landing.

The high level of integration and collaboration with elements internal and external to the J-UCAS system drive the need for a common operating system. The common operating system enables the required integration and interoperability in a network centric approach. As such, each element in the system is a node, which can both communicate to and from any other node. Examples of nodes are the flight management system, weapons, and sensors of each UAV member within the J-UCAS system. An example of a node external to the system is the ground operator. The common operating system provides the interfaces between these nodes and the means to manage the nodes. The common operating system also provides and manages the communication links between members within the J-UCAS system. A standard architecture for plugging into the common operating system increases the platforms availability for missions and reduces operating costs.

J-UCAS has been revised and reprogrammed from its initial requirements. No longer an on-going project as originally envisioned, it technologies have “morphed” into other military applications. Conceptually, this application faced significant technological challenges.

Appendix C

UAV Mission Descriptions

A list of representative missions has been compiled and is described in the following sections. It is recognized that this list is not comprehensive; additional efforts will be completed in future versions of this report. Missions have been divided into the categories defined by Figure 1.1, i.e., Earth Science, Land Management, and Homeland Security. Missions are not listed in any particular order within each category. Within each mission section, the paragraphs will address:

1) The mission description, benefits and justification
2) The platform operational requirements
3) The payload attributes and requirements
4) The communication requirements

No commercial missions have been documented to date although preliminary discussions indicate that a significant number of these exist including precision agriculture. Commercial missions will be addressed in future updates of this document.

C.1 Earth Science UAV Missions

Mission C.1.1: Repeat Pass Interferometry for Surface Deformation

Source: NASA Science Mission Directorate / Earth Surface and Interior Structure Focus

This mission would allow measurement of the geophysical processes associated with natural hazards such as Earthquakes, landslides, and volcanoes as they are manifested by deformations in the Earth's crust. Measurements of the crustal deformation would be made by an interferometric synthetic aperture radar (SAR) carried by the UAV platform. The benefits of these measurements include:

- Driven by slow plate motions, rapid injection of magma into the plumbing system of a volcano can lead to explosive eruptions over hours to days. Measurements from this system will lead to better models of the internal plumbing and magma flow within a volcano.
- Steady slip along a fault in the crust can lead to sudden, major Earthquakes and days of continuing slip. Using measurements from this system, a better understanding and assessment of the rate of slip and rebound surrounding a seismic event can be obtained.
- Gradual movement of hillsides as a result of heavy rainfalls may eventually lead to catastrophic landslides. Accurate measurements of surface deformation over areas prone to landslide will assist in assessment of the process.

Interferometric measurements would be made by flying a single aircraft along a precisely defined trajectory or by a pair of aircraft flying in a precision formation. Passes would be made days or weeks apart to monitor the change in topography.

The aircraft platform should be able to fly a defined trajectory within approximately ±16 feet (±5 meters) accuracy. The platform must be able to fly above normal air traffic; approximately 45,000 feet (14 kilometers) is desired. The platform should be capable of flying in a variety of weather conditions and operate from conventional airports. The aircraft should have a minimum range of 2000 nautical miles (3700 km). The aircraft must also provide the ability to mount an external, side-looking, active array antenna (1.6 ft by 6.5 ft (0.5 m by 2.0 m)) without obstruction.

Payload weight and volume are estimated to be 660 pounds (300 kilograms) and 35 cubic ft respectively (one cubic meter). Two thousand watts of direct current power are estimated to operate the radar.

The aircraft will require a low-bandwidth, over-the-horizon (OTH) communication link to support radar operation and health/status monitoring (a high-bandwidth capability would be an asset).

Mission C.1.2: Cloud and Aerosol Measurements

Source: NASA Science Mission Directorate / Atmospheric Composition Focus
This suborbital mission would study transformations of aerosols and gases in cloud systems in the following domains:

- Convective systems: to include areas of Costa Rica, Southern Florida, and Central United States
- Sea breeze cloud formation – wide areas of coastal U.S.
- Marine stratiform – primarily the California coastal areas
- Contrails in the Central U.S. in air traffic regions and ship tracks in oceans
- Synoptic scale systems & Fronts – in the Central U.S. region
- Cirrus outflow – large areas of the tropics, Southern Florida, and Central U.S.

To accomplish this mission, formation flying of four vehicles would be required – three for *in situ* sampling of the in-flow region, out-flow region, and convective core, and one for high altitude remote sensing aircraft (near tropopause). This formation would allow profiling of cloud and clear sky environments (optical, composition, and microphysical parameters) to examine variability of aerosols and direct and indirect chemical and radiative effects of clouds and aerosols.

In addition, investigations of the fundamental microphysics of cloud drop formation and evolution could be accomplished by looking at inflow and outflow through these systems to see the transformations. For example, the sensors would determine differences in the inflow into cumulus convection in the boundary layer and lower troposphere and the outflow in the mid-to-upper troposphere. Aerosols and pollutants are modified by these convective systems as they are lofted into upper troposphere/lower stratosphere. It is expected that these flights may occur in severe convective environments (i.e., strong vertical wind shear, severe lightning). Observations of these aerosol and cloud events could be made synergistically with inputs from satellite platforms.

In the performance of this mission the *in situ*, in-flow measurement platform is required to fly between the surface and 20,000 feet (6 km). As such, its vehicle management system should employ terrain avoidance. The other *in situ* platforms are required to fly between 20,000 and 60,000 feet (6 km and 18 km). And the remote platform must fly between 40,000 to 60,000 feet (12 km to 18 km). All platforms are required to have a range of 6000 nm (11100 km) and an endurance of 24 hr. Although the vehicles would operate with pre-programmed profiles, their vehicle management systems must support re-tasking during the mission. The *in situ* vehicle management system must be able to receive re-tasking commands from the remote platform. The *in situ*, convective platform must be sustainable in severe turbulence (165 ft/sec, 50 m/sec downdraft), lightning strikes, and large hail. The platforms must be available for a 4 week campaign where 3 flights per week are flown.

All instrument payloads for these missions would have dedicated computation and data storage. Aircraft data inputs such as altitude, attitude, latitude, longitude, speed and time are required for data analyses. The typical sensor suite for the remote sensing vehicle would be nine instruments with a total weight of 2000 lbs (900 kg). The necessary volume for the suite would be around 150 ft^3 (4.25 m^3). Some of the sensors will require unrestricted ports for accuracy. The *in situ* measurements platforms would have between 14 and 24 instruments (depending on focus with a weight range between 1600 lbs and 2800 lbs (725 and 1275 kg). The volume for the instruments would be less than 180 ft^3 (5 m^3). The operating environmental conditions require free stream sampling, no pressurization, some air flow scoops and venting. Instrument cooling may be a major issue for tropospheric sampling and active temperature control may be necessary.

Since optimal mission achievement requires in-flight re-tasking in near-real-time, over the horizon (OTH) communications capabilities are essential. This re-tasking of the vehicle would occur in mid-flight as meteorological, cloud, and near real-time radar imagery evolves. It is estimated that a minimum data rate of 9600 baud for the instruments would be needed.

Mission C.1.3: Stratospheric Ozone Chemistry

Source: NASA Science Mission Directorate / Atmospheric Composition Focus
The purpose of this mission is to observe changes in the stratospheric ozone chemistry by the profiling of source gases, water, aerosols, and temperatures in the mid-latitudes and Polar Regions in the upper troposphere/lower stratosphere. In addition to source gases, tracers as well as reservoir species and radicals are to be measured. The mission will make simultaneous measurements of water vapor, total water temperature, pressure, winds, ozone, aerosols, and polar stratospheric clouds (PSC). Part of this study will be to determine whether the stratospheric ozone layer (i.e., Antarctic ozone hole, Arctic ozone levels, mid-latitude) will recover to pre-1980 levels and how climate change will interact with the expected decrease of ozone-depleting substances. An alternative scenario for this mission might be to split the payload into *in situ* and remote sensing instruments and to fly these payloads in formation on separate aircraft. In this mode, the *in situ* vehicle's measurements would be taken simultaneously with those in the remote sensing platform and correlated with each other.

The platforms must provide long range (>13000 nm, 24000 km), long duration (2 – 5 days), high altitude (70,000 ft, 21 km), and heavy lift capability. Cruise speed must be between Mach .4 to .7. In addition the platforms must be highly reliable, 1000 flight hours over a 4 month period, and they must conduct missions at a frequency of 1 per week during a 1 month campaign.

These measurements will be accomplished by both *in situ* and remote sensing suites of instruments. The 21 *in situ* instruments will have a total weight of 2500 lbs. (1125 kg) and a volume of 150 ft^3 (4.25 m^3). The 6 remote sensing instruments will have a total weight of 1000 lbs (450 kg) and a volume of 75 ft^3 (2.1 m^3). Additional support of the mission includes:

- All instruments with dedicated computers and data storage.
- Aircraft performance data (altitude, latitude, longitude, time, attitude) required by the instruments.
- Experimenters will need easy access to instruments, and instruments with capability to be off-loaded from aircraft after each flight.
- All instruments' weight, volume, and power estimates are based upon current capabilities.
- Environmental conditions – free stream sampling, no pressurization, some air flow scoops and venting.

Real-time communication for re-tasking aircraft in mid-air during the mission as meteorological, PSC, and chemical forecasts evolve as well as OTH communications capability are essential. The OTH network requires a minimum baud rate of 9600.

Mission C.1.4: Tropospheric Pollution and Air Quality

Source: NASA Science Mission Directorate / Atmospheric Composition Focus
The objective of this suborbital mission is to study the sources, evolution, and distribution of tropospheric pollutants. The pollutants and particles and their source emissions would be profiled on regional to hemispheric scales from near the surface to the tropopause region. This profiling would cause determination of where plumes of pollution are transported and how they evolve.

The mission would involve formation flying of four aircraft platforms for *in situ* measurements in the boundary layer, mid-tropospheric and upper tropospheric regions and a high altitude remote sensing platform (near tropopause). This type of formation would begin with a pre-programmed scenario with the capability of re-tasking during the mission. The aircraft formation would follow plume events over several days and over several thousand km. The observation data of these plume events would be combined with data from geostationary platforms.

The platforms required to do this mission should have a range of 8100 nm (15,000 km) and an endurance of 2 to 4 days. Remote sensing vehicles should operate at 40,000 to 60,000 feet (12 km to 18 km). The *in situ* vehicles operate from near the surface to 60,000 ft (18 km). The *in situ* vehicle management system should be able to receive re-tasking commands from the remote platform. In addition the platforms should be highly reliable, 1000 flight hours over a 4 month period, and they should conduct missions at a frequency of 1 per week during a 1 month campaign. Turn-around time between missions should be less than 48 hours.

The sensor suite will consist of seven instruments for the remote sensing vehicle with an expected weight of 1600 lbs (725 kg) and a volume of 100 ft^3 (2.8 m^3). The instruments required for the *in situ* measurements have an expected weight of 2500 lbs (1130 kg) and a volume of 150 ft^3 (4.25 m^3). All instruments' weight and volume estimates are based upon current capabilities. Additional mission support factors are:

- All instruments with dedicated computers and data storage.
- Aircraft performance data (altitude, latitude, longitude, time, attitude) required by the instruments.
- Experimenters will need easy access to instruments, and instruments with capability to be off-loaded from aircraft after each flight.
- Environmental conditions – free stream sampling, no pressurization, some air flow scoops and venting.

Over the horizon communication and control of the aircraft by ground base is required. Also necessary is the capability for near real-time re-tasking based upon observations from the remote sensing platform. The minimum acceptable baud rate is 9600.

Mission C.1.5: Water Vapor and Total Water Measurements

Source: NASA Science Mission Directorate / Atmospheric Composition Focus
The objective of this mission is to study water vapor and total water in the tropical tropopause layer. The focus will be to profile water from the mid-troposphere to the lower stratosphere and from the tropics into the mid-latitudes. This study will try to determine what controls upper troposphere/lower stratosphere water and how it impacts climate change feedbacks. The study will utilize two platforms for the measurements: one for the *in situ* platform instruments in the upper troposphere/lower stratosphere; and one for the remote sensing platform instruments that will be in the stratosphere.

The platforms to perform this mission require 22,000 nm (40,000 km) range capability and 3 to 5 days endurance capability. Both aircraft platforms will operate between 30,000 and 70,000 feet (9 and 21 km). The platform must have high reliability, that is, the aircraft must be able to conduct 2 to 3 flights over a one month campaign. The vehicle management systems of both platforms must work together as a coordinated team, and must accept real-time re-tasking in mid-air as meteorological, cloud, and chemical forecasts evolve.

The instruments on both platforms will measure simultaneously water vapor, total water, water isotopes, temperature, pressure, winds, ozone and other gases and particles. The *in situ* platform will have available 17 instruments with a total weight of 1800 lbs (820 kg) requiring a total volume of 120 ft^3 (3.4 m^3). The five remote sensing instruments, consisting of 2 Light Detection and Ranging (LIDAR) units, 1 Fourier Transform InfraRed (FTIR), 1 microwave, and 1 drop-sonde[1] are expected to have a total weight of 1200 lbs (550 kg) using a total volume of 80 ft^3 (2.3 m^3). All instruments will have dedicated computers and data storage. Vehicle performance data (altitude, latitude, longitude, time, and attitude) will be required by the instruments. Experimenters will need easy access to instruments, and instruments will probably be off-loaded from aircraft after each flight. All instruments' weight and volume estimates are based upon current capabilities. Additionally, the operating environment will require free stream sampling, no pressurization, air flow scoops and venting. Some ports and side window for LIDAR, microwave and FTIR will be needed.

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[1] Several of the missions originally referred to the drop-sonde concept in a variety of terms such as sonde or smart-sonde. To keep consistent terminology the term 'drop-sonde' will be used throughout this report.

Real-time re-tasking of the aircraft requires an OTH network capability with a minimum of 9600 baud rate.

Mission C.1.6: Coastal Ocean Observations

Source: NASA Science Mission Directorate / Carbon Cycle, Ecosystems, and Biogeochemistry Focus

This suborbital mission would help scientists understand further coastal bloom compositions and the changes over time and space. In addition, the science data will help scientists quantify the submerged aquatic vegetation and coral reefs, measure an estuarine condition, and evaluate how nutrients are consumed and released into the coastal zone and the impact on the carbon cycle. The science data gathered would reduce the uncertainties in the fluxes and coastal sea dynamics by resolving horizontal and vertical resolution (improved spatial and temporal resolution) and multiple sensor integration. This approach leverages the suborbital platform inherent advantages of high frequency and high resolution measurements that can be used to resolve temporal variation in space time and spectra.

The mission calls for the aircraft platform to loiter over a particular region of interest, such as a bay, or perform transects of larger coastal regions. The science data from the suborbital platform will be integrated with a deployable underwater vehicle(s), which provides measurements such as salinity, temperature, and chemical and optical properties. The underwater vehicles will be deployed from air or land. Measurements will yield, at a minimum, a profile and quantification of the biomass, and the sea surface roughness and salinity. Primary areas of interest are the continental shelves off North America and in the tropics. Data will be gathered from 25 to 110 nm (50 to 200 km) offshore, depending on the depth of the shelf. The missions will be cued from Moderate Resolution Imaging Spectroradiometer (MODIS) / Visible Infrared Imager Radiometer Suite (VIIRS) ocean color measurements or *in situ* buoys, or following cyclone/hurricane events. Aircraft will be deployed before the bloom to observe and measure the development and waning. This mission may be flown in tandem with the CO_2 flux mission.

Aircraft platform requirements include one 24 hr mission per season, with measurements every 65 ft (20 meters). The platform should fly above 40,000 feet (12 km) to avoid commercial traffic. The vehicle management system should allow integration of payload measurements with underwater vehicles and buoys for the purposes of re-tasking.

The suborbital payload will consist of five instruments: hyperspectral sensor (350 nm to 1000 nm, 650 km to 1850 km); tunable laser diode; Terminal Imaging Radar sensor (8-12micron); a scatterometer (Ku band) for roughness; and, a microwave for salinity. The two sensors and laser diode combine for 165 lbs (75 kg) weight and 300 W required power. The microwave will be similar to that used for Aquarius satellite.

The command and control (C^2) and data telemetry will be at 20 Mbps. OTH network capability is required with near real-time communication with underwater vehicles and buoys to support flexibility in tasking.

Mission C.1.7: Active Fire, Emissions, and Plume Assessment

Source: NASA Science Mission Directorate / Carbon Cycle, Ecosystems, and Biogeochemistry Focus

This suborbital mission would help Earth Science scientists further understand the influence of disturbance on carbon cycle dynamics by observing and measuring: the atmospheric chemistry; the thermal intensity time-series; the plume composition, including the volume, albedo, particle size distribution; and, the fuel type and quality. The measurements would also provide the atmospheric composition focus area a better understanding of fire plume chemical constituents resulting from different fuels under different intensities of fire. The suborbital platform is ideally suited for these measurements because of its loitering capabilities and the fact that the plume measurements are dangerous and dirty.

The mission will be based on the fire season, which in North America is from May through September. The mission requires a flying formation of at least two platforms – one (disposable) for *in situ* plume measurements and the other, at a higher altitude, for fire dynamics. An alternative to the configuration is to drop the instruments into the plume. The mission will follow the plume and will range from the source of the plume to deposition. Deployment will be contingent upon human or satellite detection. Specifically, the deployment may be cued from:

- MODIS/VIIRS active fire detection or human detection; specific flight preparations would be determined by fire season and fire risk assessment. In addition, flights would follow dry lightning storms to search for new fires.
- A high-altitude, long duration aircraft could loiter over an area for weeks to months, wait for fire and task lower altitude assets.
- A prescribed burn that would allow for more thorough assessment of pre and post fire carbon mass balance.

The platforms must have an endurance capability of 24 to 72 hours, the typical duration of a fire. Range must be up to 5500 nm (10000 km). The *in situ* platform may also have several unique issues:

- plume sampling would require the ability of the platform to withstand extreme vertical velocities coming off the fire.
- an electric propulsion system would prevent issues associated with engine air intake and fuel flammability.
- airframe and sensor materials would need to be fire proof.

The suborbital payload for this mission will consist of three groups of instrumentation: a) isotope ratio mass spectrometers, gas chromatographer, non-dispersive infrared (IR) analyzer; b) imaging spectroscopy and c) a LIDAR. The spectrometers, chromatographer and IR analyzer will weigh between 110 and 220 lbs (50 and 100kg), and will require an accurate IMU and a 3-dimensional wind field at 10 Hz or better. The imaging spectroscopy will be less than 110 lbs (50kg), 18 ft^3 (0.5 m^3) and require 200 W. The LIDAR will be a waveform and will be able to resolve particles ranging from less than 0.05micron – 20 microns. It will weigh approximately 66 lbs (30kg) and require 600 W. Both the imaging spectroscopy and the LIDAR require downward looking ports. The imaging spectroscopy will have a 16 to 66 ft (5 to 20 m) horizontal and a 2.7 to 27 nm (5 to 50 km) swath; the LIDAR will cover a 3.25 ft (1 m) horizontal, 0.5 ft (15 cm) vertical and less than 1.6 nm (3 km) swath.

The C^2 and data telemetry will require OTH capability. In addition, real-time data would be telemetered to the field.

Mission C.1.8: O2 and CO2 Flux Measurements

Source: NASA Science Mission Directorate / Carbon Cycle, Ecosystems, and Biogeochemistry Focus

This suborbital mission would help scientists further understand the flux of O_2 and CO_2 and other trace gases between the surface (land and sea) and atmosphere and how it changes with space and time. Diurnal time series measurements of surface to atmosphere gas flux are critical. Specifically, the mission must provide science data that contains CO_2 and O_2 measurements, separating out land from ocean fluxes, to less than 0.1 parts per million. The data must have a vertical resolution of column CO_2 that is expressed as a function of atmospheric pressure gradients, with resolved differences as low as 10 millibar and a horizontal resolution of 328 ft (100 m) for interferometer and 33 ft (10 m) for flux measurements.

These observations and measurements will support the carbon cycle science focus area roadmap. They will provide higher resolution data on sources and sinks of atmospheric CO_2 on land and in the ocean and information to scale up flux measurements from tower networks.

Flight characteristics will include multiple platforms, depending on the complexity of the mission, that resolve horizontal distribution and errors introduced by advection. Scientific measurements will be global (land and sea) and seasonal. The mission flight path will vary according to changes in weather, input from *in situ* sensors, and other UAVs in swarm, etc. Flight profiles and maneuvers in time, space and geographic coordinates include:

- multiple altitudes, either by ascending spiral or stacked array
- flying as low as possible, appropriate to regime being measured by the interferometer
- determining the speed as a function of the integration time of instruments
- determining airspeed as a function of the speed of the air mass being measured
- establishing a racetrack pattern to follow the air mass.

One unique mission issue is the fact that the land fluxes are 10 to 50 times greater than the ocean fluxes.

This mission places the following requirements on the platforms: The platforms must have a 24-hour endurance capability to obtain data for diurnal patterns. The platforms will have a pressurized, temperature controlled hard-drive for on-board data storage. The vehicle management system must provide for coordinating multiple platforms and inputs from several sources. The system must also provide for low altitude flight down to 328 ft (100 m), thereby requiring terrain avoidance algorithms.

The suborbital payload will consist of two groups of instrumentation: isotope ratio mass spectrometers, gas chromatographer, non-dispersive IR analyzer; and an upward-looking Michelson interferometer in the 4 micron band. The spectrometers, chromatographer and IR analyzer will weigh between 110 and 220 lbs (50 and 100 kg), and will require an accurate IMU and a 3-dimensional wind field at 10 Hz or better. The upward looking Michelson interferometer will weigh approximately 110 lbs (50kg), have an upward viewing port and fly in an attitude as low as possible.

The C^2 and data telemetry will require OTH capability for control and data relay. The data rate is expected to be greater than 1 Mbps.

Mission C.1.9: Vegetation Structure, Composition, and Canopy Chemistry

Source: NASA Science Mission Directorate / Carbon Cycle, Ecosystems, and Biogeochemistry Focus

This suborbital mission would help scientists improve the characterization of terrestrial biomass, leaf level chemistry and canopy water content. The science data will provide vegetation 3-dimensional structure and information on composition and chemistry. In addition, the observations will elucidate functional groups and physiological impacts on the carbon cycle.

The missions will include observations at flux tower locations and long term ecological experiments and ecological transects along ecological gradients. Collection opportunities will be optimized using meteorological data. To accomplish the mission, the formation will require 3 to 7 platforms each carrying P/L band radars and a subset carrying hyperspectral and LIDAR instruments. Weekly, during all seasons, the missions will cover major ecological biomes distributed worldwide.

To perform this mission the platforms will be required to cruise at approximately 40,000 ft (12 km) with an endurance of between 12 and 24 hours. The platforms will be in straight and level flight with sufficient geolocation and attitude through Global Positioning System (GPS) or metrology.

The payload will consist of four instruments: a) Radar: interferometric, weighing less than 660 lbs (300 kg), less than 35 ft^3 (1 m^3), 2 to 3 kW, 16 to 32 ft (5 to 10 m) horizontal, 3.3 ft (1 m) vertical and 2.7 to 11 nm (5 to 20 km) swath; b) Imaging spectroscopy, a hyperspectral sensor (350 nm to 2500 nm, 650 km to 4600 km), weighing less than 110 lbs (50 kg), 16 ft^3 (0.5 m^3), 200 W with a downward-looking port, 16 to 66 ft (5 to 20 m) horizontal and 2.7 to 27 nm (5 to 50 km) swath; c) LIDAR: two frequency (1700 ft (525 m), 1050 nm (1950 km)) digitized waveform, weighing less than 66 lbs (30 kg), approximately 600 W of power, downward-looking port, 3.2 ft (1 m) horizontal and 0.5 ft (15 cm) vertical with less than 1.6 nm (3 km) swath; and d) Very High Frequency (VHF) antenna, details to be defined.

Mission achievement requires OTH communications capabilities; with telemetry and C^2 rates at 1 Mbps. In addition, precise position and attitude information to the level of sub-meter positioning for GPS (1 ft, 30cm); 5-10 arc sec attitude knowledge and active metrology for radar implementation will be needed.

Mission C.1.10: Aerosol, Cloud, and Precipitation Distribution

Source: NASA Science Mission Directorate / Climate Variability and Change Focus

This mission is designed to measure the distribution in space and time of aerosols in regions polluted by industrialized areas. The data collected during this mission will improve the evaluation of climate sensitivity to the forcing of aerosols by:

- Quantifying how urban aerosol sources contribute to global aerosol budgets and loading,
- Detecting the indirect effect of anthropogenic aerosol on cloud formation and radiative forcing,
- Detecting multi-year to decadal trends in direct and indirect aerosol forcing, and,
- Developing a statistical data base of pollution impacts downstream of pollution sources.

Other areas impacted by these observations include water cycle variability, regional weather, cloud and precipitation, and the carbon cycle through absorbing aerosols.

This mission requires the UAV platform to follow a pollution stream and collect spatially varying data on the chemical evolution and aerosol formation in the air. The UAV mission will range from 110 nm (200 km) upstream from a pollution source to 1100 nm (2000 km) downstream of that source. At various points downstream (5.5, 27, 135, and 675 nm) (10, 50, 250, and 1250 km), the aircraft will perform vertical and cross-track profile measurements. Flights will take place mainly in urban centers around the globe, but may also include flights into remote tropical and temperate latitudes. In some locations, a sampling of the cloud systems may be desirable. To reconstruct the evolution of polluted air for a variety of meteorological conditions, this mission should be repeated daily at a given source for a minimum of three weeks. To detect trends in the multi-year time scale, this set of missions should be completed once a year. A large number of flights (about 10000 flight hours) over several years are required to collect the desired data, therefore it is critical to keep the cost per flight hour low (< 1000 $/hr). In general, the statistical nature of climate studies requires low flight hour costs.

Other variations of the mission are also postulated. Simultaneously collecting data along the direction of the pollution transport would be ideal. This would require multiple aircraft (possibly a piloted and unpiloted mixture) deployed from different locations working in close coordination. Another variation of the mission is to measure temporal effects by collecting data over a diurnal cycle at each measurement location.

The mission requires the vehicle's flight management system to allow a ground commanded re-direction of the flight path during the flight. Also, since data collection occurs near urban pollution sources, air space access for UAVs and cooperation with air traffic control is necessary. The platform's range must be a minimum of 1100 nm (2000 km). The platform must be capable of maneuvering between 2,000 and 60,000 feet (0.61 and 18 km) to sample cloud systems. Endurance requirements, based on the diurnal cycle mission variations, are 20 to 30 hours. In addition, mission variations require the vehicle management system to allow multiple platform coordination.

To perform the mission, the platform must carry a large variety of payload sensors as listed: scanning polarimeter, atmospheric gas and particle samplers (e.g. mass spectrometer), broadband and spectral flux radiometers with precise attitude measurements (< 0.1 degree from horizontal), interferometer for measuring water vapor, LIDAR, cloud radar, and simple imagers. Payload weight is anticipated to be 1100 lbs (500 kg) and power requirements are 5 to 10 kW. Some external sampling probes and up and down looking ports must be provided.

Since data monitoring requirements are primarily for the purpose of quality assurance, the aircraft must only support low communication bandwidths. However, an OTH communication network may be required, which supports operations in remote locations.

Mission C.1.11: Glacier and Ice Sheet Dynamics

Source: NASA Science Mission Directorate / Climate Variability and Change Focus

This mission supports measurements of the dynamics of the breakup of polar glacier and polar ice sheets. The measurements enable direct observation of the evolution in time of ice and land topography, iceberg volume, glacier profiles, and glacier channel profiles and provide data for validating simulations of these dynamics and their interaction with the ocean environment. Other benefits include measures of the impacts on ocean currents, regional weather and climate, water cycle variability, and clouds and precipitation.

To understand the impact of ice sheet dynamics on various systems the initial states of those systems must be measured. Thus, this mission requires two phases. The first phase involves initial mapping and documenting of the Polar Regions, particularly those where breakups are anticipated (e.g. Larsen C in Antarctica). This phase, in particular, involves a relatively large number of flight hours. As such low costs per flight hour (<1000 $/hr) and quick turn-around times between flights (or multiple platforms) are critical. The second phase occurs when the beginning of a breakup is detected. At that point a quick deployment of the platform and its support equipment to the nearest serviceable airport is necessary. Unique characteristics of this mission will include dropping buoys for ocean measurements, and dropping radio frequency transponders on large icebergs that break off the ice sheet for tracking purposes. After collecting data during the break-up a final mapping and documenting of the polar region occurs.

For both phases of the mission the platform must have the range to reach any part of either polar region from a base of operations, with an endurance of up to 24 hours. High altitude flight is not required, but variations in altitude from 12,000 feet (3.6 km) to 20,000 feet (6.1 km) are. Turn-around times between flights should allow the platform to be available for a mission at least 50% of its deployment time. During the ice breakup, the platform should be able to perform 1 mission every 3 days over the course of a 2 month campaign. During the second phase, the ability to upload a new flight profile to the vehicle's flight management system to re-task the platform while in flight is critical for catching interesting dynamic events as they develop. The platform must provide for deployment of drop buoys as well.

Because of the large variety of measurements required, e.g. ocean salinity, temperature, and current flow both at the surface and at iceberg depths; a host of sensor payloads are carried by the platform. These are listed as follows: radar depth sounder, scanning LIDAR, drop buoys, drop-sondes, microwave sounder, radio frequency transponders for tracking icebergs, magnetometer, atmospheric gas and particle samplers, and simple imagers. Anticipated payload weight is 1000 lbs (454 kg) and power requirements are 10 kW.

An OTH network to support data quality assurance is required, but data bandwidth can be low.

Mission C.1.12: Radiation - Vertical Profiles of Shortwave Atmospheric Heating Rates

Source: NASA Science Mission Directorate / Climate Variability and Change Focus

This mission will collect data on the vertical profile of shortwave atmospheric heating rates in polluted and unpolluted clear and cloudy skies. Measurements will take place in mega-cities and industrialized regions in different climatological regimes. The data collected will improve the evaluation of climate sensitivity to the forcing of aerosols by:

- Quantifying how urban aerosol sources contribute to global aerosol forcing
- Detecting the indirect effect of anthropogenic aerosol on cloud radiative forcing

The data also impacts weather forecasting, the role of heating rates in cloud and precipitation processes, carbon cycles through absorbing aerosols, and the capability for detecting bio-aerosol sources and dispersion.

The mission concept calls for a major platform to make cloud and aerosol state parameter measurements and up to ten Mini Aerial Vehicles (MAVs) platforms to make radiative flux measurements. A geographic point of interest within a region is selected and the major platform is launched and flown to that point. At that time either the MAVs are launched from the major platform, or the MAVs are launched separately and rendezvous with major platform. In either case each of the smaller UAVs are assigned to hover or circle at a given altitude to form a column around the point of interest. The major platform then flies in upward and downward spirals around the column. After data is collected the mission is repeated at another point of interest within a 54 nm by 54 nm (100 km by 100 km) region of interest. Collection of 50 sets of data within a region is desired. To get the effects due to varying weather conditions the mission is repeated on a near daily basis. Many flight hours are required to perform this mission in order to obtain statistically meaningful data across a variety of aerosol types and meteorological conditions. A low cost per flight hour is essential (<1000 $/hr).

The platforms in support of this mission must be capable of flying between the surface and 60,000 feet (18.3 km). The MAVs must be able to hover over a geographic location within a 328 feet (100 meter) radius at a given altitude. On-station endurance for both platforms is 6 hours for one set of data, centered on solar noon. Vehicle management system for the major platform must allow re-tasking, while the vehicle management system on both types of platforms must allow for coordinated flying. The system must support flying within the air space and, since the major platform in particular will fly near the surface, the system should employ terrain avoidance algorithms.

Payload for the major platform consists of broadband and spectral flux radiometers with upward and downward looking ports, drop-sondes or balloon sondes for temperature and water profiles, atmospheric gas and particle samplers, LIDAR and cloud radar, and sky imagers. Payload weight is anticipated to be 660 lbs (300 kg) and total power required to be 3 to 5 kW.

Payload for the MAV platforms include broadband and spectral flux radiometers with upward and downward looking ports, temperature monitoring, a simple imager, and a transmitter to transmit data to the major platform. Payload weight is anticipated to be 22 to 44 lbs (10 to 20 kg). The total power is estimated to be 10W with a total payload volume of 7 cubic inches (100 cubic cm).

Some unique communication requirements exist for this mission. The location and altitude targets for the MAVs are uploaded from the ground to the major platform during the mission. These targets can be adjusted as the mission progresses. The major platform then communicates to each of the MAVs their assigned altitude. The data from the MAVs consists of status and information required to perform the mission as well as the payload sensor data, which is recorded on-board the major platform or down-linked for recording on a ground computer.

Mission C.1.13: Ice Sheet Thickness and Surface Deformation

Source: NASA Science Mission Directorate / Earth Surface and Interior Structure Focus

The purpose of this mission is the accurate measurement of ice sheet thickness and crustal deformation of underlying surfaces due to ice sheet loading and Earth internal activities such as Earthquakes. These measurements are important for the study of glaciers and global warming.

The approach would be to use many (> 50) MAV platforms, each carrying a synchronized VHF or Ultra High Frequency transmitter/receiver module, in formation flight. This would require relative positioning of the platforms with respect to a coordinate system to within a fraction of a wavelength. These would operate at about 500 feet (152 m) to achieve high resolution and for signal/noise considerations. The MAVs would fly parallel straight lines to get a raster image of 5.4 nm by 1 nm (10 km by 2 km).

Since flight at low altitude is required, the vehicle management system should employ a terrain avoidance algorithm. The system must also allow multi-ship coordination amongst vehicles in formation flight. The platform range requirement is estimated to be 100 nm (185 km).

Payload requirements for weight and volume would be about 7 lbs (3.2 kg) and 70 cubic inches (1000 cubic cm). The MAV platform would need to supply about ten watts of power to the payload. It would also need a relatively high data rate communication link to a satellite, base station, or mother ship for data collection, command, and control.

Mission C.1.14: Imaging Spectroscopy

Source: NASA Science Mission Directorate / Earth Surface and Interior Structure Focus

The intent of this mission is to collect spectra as images to determine surface composition, change, water vapor and sulfur dioxide in space and time. Specifically, this mission would measure:

- the composition and change at the surface-atmosphere interface
- accurate and precise 3-dimensional water vapor for GPS based derivations
- 3-dimensional SO_2 and other phenomena associated with active volcanology
- Earthquake fault optical spectroscopy properties before and after

Baseline data would be collected and updated periodically. Phenomena (volcanic eruption, Earthquake, flood, etc) data could also be measured as desirable.

The UAV platform would fly at approximately 45000 feet (13.7 km) altitude and would need an endurance of 12-24 hours. Rapid response would be necessary to support phenomena measurements. Mission support anywhere in the world should be possible.

The payload for this mission would weigh about 110 lbs (50 kg) and would require the volume of about 17.6 ft^3 (0.5 m^3). About 200W of power would be required. A down-looking port is also necessary.

Real-time communication for quick-look data is required.

Mission C.1.15: Topographic Mapping and Topographic Change with LIDAR

Source: NASA Science Mission Directorate / Earth Surface and Interior Structure Focus

The purpose of this mission would be to generate high-resolution topographic mapping and topographic change-detection of targeted ground areas (including those covered by vegetation) using LIDAR measurements. All-terrain topographic change detection by repeat mapping compliments interferometric SAR measurements of sub-centimeter to decimeter surface levels (e.g., observe decimeter to tens of meter near-field surface deformation in the vicinity of ruptured faults and inflating volcanoes to understand Earthquake and magmatic processes; observe decimeter to hundreds of meters topographic change associated with landslides, volcanic eruptions and flows, coastal and fluvial erosion and sediment redistribution). Targets of highest priority are narrow, long, quasi-linear features (e.g. fault zones, coastal zones) amenable to targeted mapping or point features (e.g. volcanoes) amenable to station-keeping monitoring. The mission requires data to be collected over a series of offset, parallel, overlapping flight tracks to build up a corridor of data covering the region of interest.

To collect the desired data the platform should operate at a constant altitude of 65000 feet (19.8 km) with a ground speed of about 200 knots (100 m/sec). Target positioning (achieved by combination of platform navigation and sensor steering to compensate for platform roll) should provide a ground track with cross-track accuracy of 490 ft (150 m). Precision knowledge of the flight path (2 inches) (5 cm) and sensor attitude (5 arc sec) is required for post-mission processing of the data. Platform range should be on the order of 2000 nm (3700 km). The platform should be capable of autonomous operation with human intervention and should provide on-board intelligence with operational limits for instrument health and safety as is done for orbital instruments. The platform’s vehicle management system must be able to optimize flight path based on weather and cloud cover information to acquire data in clearest areas.

The primary payload is a geodetic imaging LIDAR (i.e., scanning laser altimeter) capable of 1.5 million range observations per second (1.6 nm (3 km) swath width, 5 returns per 3.28 ft (1 m) pixel, & 200 knots (100 m/sec) ground speed). Based on expected advances in instrument technology, the expected weight, volume and power requirements are 65 pounds (30 kg), 2.5 cubic feet (64000 cm^3), and 200 watts respectively.

Low-rate, OTH communication is required for performance assessment and C^2. A high-bandwidth (megabits/second) data downlink is also required for time intervals on the order of a day. Full-rate data should be stored on board for retrieval at the end of a flight. A sensor web implementation is needed to autonomously provide weather and cloud cover information to the platform.

Mission C.1.16: Gravitational Acceleration Measurements

Source: NASA Science Mission Directorate / Earth Surface and Interior Structure Focus

This mission would accurately measure gravitational acceleration that varies spatially and temporally near Earth, as a consequence of the non-homogeneity and the dynamics of Earth's mass density structure. This spatial variation occurs at all scales, from thousands of kilometers, due to core/mantle boundary anomalies, to sub-kilometer and smaller, due to local topographic (or bathymetric) masses. Earth's gravitational field defines satellite orbits, affects inertial navigation, reflects oil and mineral deposits, and characterizes crustal geologic structure. The equipotential surface, known as the geoid, defines a reference for sea surface topography (leading to oceanographic current determination through satellite ocean altimetry), and it defines the conventional reference of heights for national vertical geodetic control.

The UAV platform would fly a grid pattern at 15,000 to 30,000 feet (4.5 to 9 km) altitude utilizing long (~60 nautical miles (111 km)) straight tracks. The accuracy requirements for trajectories are on the order of 100 feet (30.5 m). Time synchronization with GPS time is critical, and geospatial registration is required to an accuracy of 10 feet (3.1 m).

Simple gravimetric systems weigh about 20 pounds (9.1 kg), require about 0.4 cubic feet of volume (.01 m^3), and consume about 20 W of power; higher accuracy units require more of each capability, and specialized, high-cost measurement units are also available.

Real-time data transmission to a base station is not required, since post-mission processing of data is the common application, but on-board data recording is necessary.

Mission C.1.17: Antarctic Exploration Surveyor

Source: NASA Science Mission Directorate / Earth Surface and Interior Structure Focus

This mission would provide coordinated magnetometer, gravity, and LIDAR measurements from a small, easily deployed autonomous low-cost aircraft platform. These measurements would allow basic mapping to determine ice sheet bed characteristics and ice sheet elevation. This data would allow scientists to examine the geologic controls on ice sheet dynamics.

To perform this mission flights would be conducted from the coast into the interior at a low altitude, thereby setting the range requirement for the platform. One concept would be to deploy from an ice breaker, which would allow a lower range (~500 nautical miles (925 km)) to be used.

The UAV platform payload would include a lightweight compact vector or scalar magnetometer, a strap-down gravity measurement system, and a small LIDAR system.

A low-data-rate telemetry system would be required for communication purposes.

Mission C.1.18: Magnetic Fields Measurements

Source: NASA Science Mission Directorate / Earth Surface and Interior Structure Focus

The purpose of this mission would be to measure vector and tensor magnetic fields to support comprehensive magnetic field source models and isolate time-varying crustal field components. The magnetic field spectrum is under-sampled in the spatial wavelengths intermediate between the near-surface (up to 1.1 nm (2 km)) and satellite altitude (190 nm to 380 nm) (350 to 700 km). These measurements are critical to producing models that account for all sources of magnetic fields from crust to core.

Flight scenarios could range from a calibrated vector magnetometer on a single UAV platform, to simultaneous measurements from coordinated platforms over a wide area (thus eliminating noise from external time-varying fields), to magnetic tensor measurements using four MAVs flying in formation. Measurements would be obtained either in a grid pattern or long prescribed flight lines.

The platform is required to collect data flying a pre-designated flight plan at altitudes ranging from 3000 feet (1 km) to 100,000 feet (30.5 km). The platform should be capable of night flying, because of a preference for the quiet external field environment. Additionally, the platform would need to be magnetically quiet.

The magnetometer weight is less than 5 pounds (2.3 kg) and would require approximately 60 cubic inches of volume (983 cm^3). Instrument attitude would need to be known within a few arc-sec of accuracy. Data would be sampled in the 1 to 20 samples per second range.

The data volume is relatively low and could be stored onboard, although some low bandwidth communication for command and monitoring would be desirable.

Mission C.1.19: Cloud Properties

Source: NASA Science Mission Directorate / Water and Energy Cycles Focus

This mission is designed to collect *in situ* data on cloud microphysics. The data will allow better understanding of cloud dynamics and lead to improved weather and climate models. Weather, climate, and atmospheric composition focus areas will also benefit from the data collected in this mission.

The concept for this mission requires at least two, perhaps three, types of platforms. An imager platform hovers or circles a region of interest looking for critical environmental characteristics. It activates and then directs a second type of platform to perform spiral descents and ascents through clouds for *in situ* measurements. The capability to fly multiple *in situ* platforms (even if weighing < 4.4 lbs (2kg)) at once would increase the science return. *In situ* platforms could be tailored for specific measurements and tasked based on previous platform data. One option may be to include a third type of platform that stores and launches multiple *in situ* MAV platforms. It is desired to collect data anywhere in the globe, excluding the Polar Regions. When a region of interest develops, the entire system has to be able to be shipped to base of operations, integrated, and launched within 1 to 3 days.

The imager platform requires an ability to station keep anywhere from a low altitude of 3000 feet (1 km) to a high altitude, perhaps 82,000 ft (25 km). To obtain temporal variations the imager must have at least 24 – 48 hours of endurance. Ideally one-week endurance would provide greater return on the science. A transport range for the imager platform of 5400 nm (10,000 km) before station keeping is desirable. Storage platform requirements are the same as the imager platform. The *in situ* platform requires altitude capability from 82,000 ft (25 km) to the surface. Range and endurance can be less (perhaps on the order of 5.4 nm (10 km) range) than the imager since *in situ* platforms can be launched in succession. But the total *in situ* platform system should provide data collecting capability that is equal to the imager endurance. The *in situ* platform may require a smart system that can direct its instrumentation based on imager commands or its own sensor data. A unique requirement for the *in situ* platform is that it should not influence (via chemical or heat exhaust) its own cloud measurements as it flies through the clouds. All aircraft involved require positional accuracy to 33 ft (10m) with an attitude accuracy of 0.1 degree for the imager.

Instrumentation for the Imager platform includes a passive microwave imager with minimally a 19 to183 GHz range, but ideally a 10 to 600 GHz range, a dual-pole multiple frequency microwave radar, a LIDAR, and smart drop-sondes. *In situ* type instrumentation is required for the *In situ* platform such as cloud particle imagers.

Communication links between the imager and the *in situ* platform should be available. The *in situ* platform should send measurement data back to the imager platform data recording. Using the OTH network, it is desired to send data to a ground station for data recording and data review. Given a storage platform, additional communication between it and the imager platform would be required.

Mission C.1.20: River Discharge

Source: NASA Science Mission Directorate / Water and Energy Cycles Focus
This mission will collect data on the volume of water flowing in a river at multiple points. The data is critical for global and regional water balance studies. Other beneficiaries of this data include USGS, EPA, coastal zone studies, and floodplain mapping efforts.

To support the objective of this mission river geometry measurements and river height measurements are required. Two platforms will be utilized to collect these measurements. One platform equipped with a LIDAR, will be used to measure river geometry. The other platform, equipped with a SAR, will be used to measure river height. Three scenarios are presented to envision how this system might be used. In the first scenario the LIDAR platform is sent to fly the length of a river channel of interest. River geometry and path measurements from the LIDAR are fed back into the platform guidance routine, allowing the LIDAR to fly the platform along the river channel. After completing the flight, the data from the LIDAR platform is extracted and transferred into the radar platform vehicle management system. This platform then flies over the river in regions of interest to measure river height. The second scenario is a variation of the first one. In this scenario the radar platform flies in formation at some distance behind the LIDAR platform. In this case the geometry data from the LIDAR platform is required by the radar platform for guidance purposes. In the third scenario heavy upstream rains have occurred for a previously LIDAR mapped river. The radar platform is then deployed by itself to measure the river height dynamics. Flights during the low flow season, late summer or early fall, are best for collecting the geometry data. River heights should be measured at least once per year, especially during high flow periods. River geometry data should be collected a few times for each river, but river height data should be collected on demand, perhaps weekly.

For all scenarios the LIDAR platform must be able to fly below the clouds. The radar platform must collect data at a high enough altitude, 16,500 to 33,000 ft (5 to 10 km), for robust measurements. Accurate position knowledge is required for both vehicles. Endurance for the vehicles is established by how long it takes to fly a given river channel, and given the desired level of resolution, how long it takes to fly it's primary, secondary channels, etc.

Payload sensors required for these missions include a scanning LIDAR for the LIDAR platform and a dual-frequency radar on the Radar platform. LIDAR constraints in weight, volume, and power are 55 lbs (25 kg), 7 ft^3 (0.2 m^3), and 500W respectively. The dual frequency radar constraints for weight and power are 440 lbs (200 kg) (depending on antennae size) and 1 – 5 kW. Also, a C-band along-track radar interferometer on both platforms would allow additional calibration and cross-platform comparison.

Real-time ground station communication requirements for this mission can be of the quality assurance nature, hence low bandwidth. In the case of the second scenario real-time trajectory information from the LIDAR platform must be transmitted to the radar platform.

Mission C.1.21: Snow – Liquid Water Equivalents

Source: NASA Science Mission Directorate / Water and Energy Cycles Focus
This mission was conceived to measure the amount of water stored in the snow pack at very high spatial resolution (~ 165 ft (50m), as reported). Also, snow pack characteristics such as depth, density, wetness, age, emissivity, albedo, etc will be measured. Measuring the snow characteristics has significant application for decision makers and is important for water budget. It would allow for improvements in snow prediction as well as understanding the climate data record.

The mission can be motivated by either a seasonal event, such as a large snowfall in a particular region, or a season long monitoring of selected snow covered regions all over the globe. The platform is programmed with a flight profile based on the location of the desired region of observation. Maneuvers and flight profiles will change based on the location, but flights in mountainous terrain are required. Collecting data at low above ground level altitudes and at specific points of interest are desired. Also, at points of interest the ability to drop a drop-sonde with *in situ* measurement capability would be of interest. Limited flight path re-direction from a ground control station is required. After the mission is completed the data, recorded on-board the platform, is downloaded and the airplane turned-around for another flight within 1 hour. The platform must be available for flight primarily in the spring, but also in the winter and fall.

Specific mission requirements include the ability of the platform to fly 330 ft (100m) above ground level, within a few meters precision, in mountainous terrain, while providing a relatively stable platform (3 degrees pitch, 5 degrees roll, and 3 degrees yaw) for payload sensors. As such the vehicle management system will have complex flight path maneuvering and terrain avoidance requirements. And the management system must allow re-direction from a ground station during the flight. The platform must fly a desired track within < 33 ft (10m). And since seasonal monitoring is a key concept for this mission, a 70 – 80% duty cycle over a 6-month season is required to get sufficient coverage. Desired endurance is 24 hours, but can be relaxed for complex terrain missions. The ability to launch multiple platforms is a desired feature that would enable greater spatial coverage.

Payload instrumentation required for this mission includes a dual-frequency SAR (C and Ku band), a dual frequency radiometer (K and Ka band), a camera, and a thermal camera. Total weight is about 660 lbs (300 kg), and total power required about 1 kW. Drop-sonde *in situ* sensors would have to be developed.

A relatively low bandwidth data communication link is required for real-time quality assurance data monitoring and limited platform re-tasking during the flight.

Mission C.1.22: Soil Moisture and Freeze/Thaw States

Source: NASA Science Mission Directorate / Water and Energy Cycles Focus
This mission was envisioned for measuring surface soil moisture, deep soil moisture, and the freeze or thaw state of surface soil in the presence of vegetation. Benefits include improved water budgets and better modeling of the carbon cycle.

The mission is simply to fly the platform aircraft from the base of operations to a specified point of interest. The aircraft circles this location or flies repeated passes over this location for the purposes of collecting data. Variations in altitude between circles or passes may be required. As the mission progresses a team on the ground reviews the data and, if desired, re-directs the flight path or alters sensor specifications via an uplink capability from a ground station. After the mission, sensor data recorded on-board is downloaded quickly and the platform prepared for the next flight. An alternative to downloading on-board data after the mission is to develop the capability to download the data periodically during the mission. Geographic regions of interest include all land areas not covered by snow or ice.

To support this mission, the platform will typically fly between 3300 and 33,000 ft (1 and 10 km) in altitude, depending on the observation scale desired. A 70-80% duty cycle is required to support the mission, but for missions in remote areas the platform should have an endurance of 24 hours over the point of interest, and be capable of flying 2 to 3 times a week, as required. Ground track precision should be < 33 ft (10m) and a pointing accuracy of <0.1 degree is necessary for payload sensors. The platform systems should support high-speed download of the data, which is desirable for quick turn-around of the platform for the subsequent flight.

Payload instrumentation includes active and passive microwave with L band for measuring surface soil moisture and P bands and potentially longer wavelengths for deep soil moisture. Multi-polarization and conical scanning is desired. Total weight is less than 440 lbs (200 kg). Volume is dictated by antennae area size, typically 10.8 to 53.8 ft^2 (1 to 5 m^2). The power required, depending on the instruments, range from 1 to 5 kW.

A low bandwidth uplink command is necessary with higher bandwidth downlinks available for real-time decision making.

Mission C.1.23: Cloud Microphysics/Properties

Source: NASA Science Mission Directorate / Weather Focus
The purpose of this mission is to observe the microphysics and properties of clouds. Specifically this entails measurements of:

- Turbulence, vertical velocity
- Particle size distributions, habit, phases
- Liquid/ice contents
- Highly-accurate thermodynamic information
- Electrical and radiation characteristics

These data would provide better understanding of tropical rainfall and energy release, rain particle growth, and stratospheric water exchange enabling the improvement of satellite algorithms.

Cloud-penetrating UAV or MAV platforms might be launched from a mother ship or might take-off from the ground and fly into a cloud in formation. The platforms would be capable of different flight profiles, but would be under the supervision of a mother ship, other lead aircraft, or a ground-based control station. They would require a controlled descent and safe recovery at locations of opportunity, including automated landing site selection. These aircraft should be able to launch and fly on very short notice (2 to 3 hours).

The platforms would be hardened to severe environments (e.g. electrical, icing, turbulence). Ideally, they would fly at a slow airspeed (~100 knots (50 m/sec)), but should retain some maneuverability against headwinds. The altitude range for these UAVs would be from ground level to 100,000 feet (30.5 km). They would need a range of in excess of 500 nautical miles (925 km) and an endurance of about five hours.

They would carry particle size probes, a laser hygrometer, radiation pyrometers, electric field sensors/probes, and microwave sensors (optional).

The UAVs would require aircraft-to-aircraft or aircraft-to-ground high bandwidth/line-of-sight communications. On-board partial processing of measurements may also be required.

Mission C.1.24: Focused Observations – Extreme Weather

Source: NASA Science Mission Directorate / Weather Focus
The purpose of this mission would be to accomplish process studies involving severe and hazardous weather events to improve the physics in mesoscale models (parameterizations). This approach would use high altitude remote sensing to gather data on precipitation, clouds, electrical phenomenon, and microphysics. These data would improve models used to predict winter storm hazards and provide accurate regional forecasting of rain and snow for economic decisions.

The UAV platform for this mission would fly at altitudes of 50,000 (15.2 km) to 65,000 feet (19.8 km) and would have a range of approximately 1000 nautical miles (1850 km) with an endurance of 1 to 2 days for continuous coverage of the storm event. The platform would be autonomously guided by satellite and ground-based measurement systems using targeted and adaptive operation with possible real-time human intervention.

Sensors would include remote sensing of temperature and water vapor, a radar and radiometer for clouds and precipitation, sensors for electrical activity and lightning, and drop-sondes when possible. It is expected that these sensors would weigh approximately 1000 pounds (455 kg) and would require 1 to 2 kilowatts of power. Appropriate viewing ports would be necessary. A pod may be necessary to carry the drop-sondes.

Communication rates on the order of 300 kilobits/second are required to telemeter data in real-time. On-board processing of the merged sensor data may also be required. Real-time control of the instruments (at a low bandwidth) will also be needed.

Mission C.1.25: Forecast Initialization

Source: NASA Science Mission Directorate / Weather Focus
The intent of this mission is to gather data that will improve weather forecasting and augment data available from satellites. This includes both a research element such as determining data sensitive regions (e.g. THORPEX, atmospheric rivers) and an operational element (e.g. NOAA/NCEP winter storms program). Missions would include observations would be made for short term (24 hour) initialization where observable events were already formed, and longer term (3 to 7 days). Additional benefits would include satellite validation (e.g. GPM and GIFTS) and the improved use of satellites for forecasting. The use of UAVs provides an opportunity for measurements from vertical profiling that are not available from satellites. Missions would be event oriented with the Eastern Pacific, Northern Atlantic, and Arctic/Antarctic as probable target areas.

Several types of platforms would be used for this mission. A mother ship would fly at high altitudes (~50, 000 feet (15.2 km)), with an endurance ranging from twelve hours to several days. Platform range would need to be better than 1000 nautical miles (1850 km). At least two tropospheric and five boundary layer aircraft would be required for supplemental measurements. The tropospheric aircraft would need to fly in the 20000 to 40000 feet (6.1 to 12.2 km) range; the boundary layer aircraft would fly between 500 feet (.15 km) and 20000 feet (6.1 km). Daughter ships would need to be rugged with all-weather performance during lightning, icing, graupel, turbulence. The daughter ships would need to be autonomously controlled in formation flight by a lead entity: a satellite, the mother ship or a ground control station but would allow for human intervention. The daughter ships could be expendable, but would preferably be re-dockable to the mother ship so that they could be reused. An alternative to daughter ships would be drop-sondes.

Sensors for the high-altitude aircraft would include *in situ* meteorological measurements, remote sensing of temperature and water vapor, a radar and radiometer for clouds and precipitation, sensors for electrical activity and lightning, sensors for surface wave spectra (GPS reflectance, LIDAR), and instruments for visible imaging for eye wall (Rossby waves). Appropriate viewing ports would be necessary. A pod may be necessary to carry the drop-sondes. The total payload weight would be on the order of 1000 lbs (455 kg). Sensors for the tropospheric aircraft would be similar to instrumentation found on drop-sondes. Boundary layer aircraft would carry an infrared pyrometer, an instrument to measure *in situ* winds (new instrument development), an instrument for surface imaging (visible), a sensor to measure turbulent fluxes (new instrument development), and other instruments commonly found on a meteorological drop-sonde.

Communication rates on the order of 300 kilobits/second are required to telemeter data in real-time. A wide-band, line-of-sight data link will be necessary to coordinate data. On-board processing of the merged sensor data may also be required. Real-time data assimilation into forecast models would be the goal. Real-time control of the instruments (at a low bandwidth) will be needed.

Mission C.1.26: Hurricane Genesis, Evolution, and Landfall

Source: NASA Science Mission Directorate / Weather Focus
The purpose of this mission would be to accomplish observations of hurricanes to improve predictions of hurricane paths and landfall. This approach would use high altitude remote sensing to gather data on precipitation, clouds, electrical phenomenon, microphysics, and dust. Daughter ships or drop-sondes would gather data (four-dimensional cubes of thermodynamic variables and winds) at lower altitudes. Additional data would be gathered in the boundary layer (sea surface temperature and surface winds, surface imaging, turbulent fluxes, water surface state). Measurements of this type would improve hurricane modeling capability to increase human safety.

Several types of UAV platforms would be used for this mission. A mother ship would fly at high altitudes (~65,000 (19.8 km)) above the storm. Mission durations would be on the order of two to three weeks, but could be accomplished with multiple platforms with less endurance capability. Aircraft range would need to be better than 1000 nautical miles (1850 km). At least two tropospheric and five boundary layer aircraft would be required for supplemental measurements. The tropospheric aircraft would need to fly in the 20,000-40,000 feet (6.1 to 12.2 km) range; the boundary layer aircraft would fly between 500 feet (.15 km) and 20,000 feet (6.1 km). Daughter ships would need to be rugged with all-weather performance during lightning, icing, graupel, turbulence. The daughter ships would need to be autonomously controlled in formation flight by a lead entity, a satellite, the mother ship or a ground control station but would allow for human intervention. The daughter ships could be expendable, but would preferably be re-dockable to the mother ship so that they could be reused. An alternative to daughter ships would be drop-sondes, although many would have to be carried by the mother ship to provide measurements for two weeks.

Sensors for the high-altitude aircraft would include *in situ* meteorological measurements, remote sensing of temperature and water vapor, a radar and radiometer for clouds and precipitation, sensors for electrical activity and lightning, sensors for surface wave spectra (GPS reflectance, LIDAR), and instruments for visible imaging for eye wall (Rossby waves). Appropriate viewing ports would be necessary. A pod may be necessary to carry the drop-sondes. Sensors for the tropospheric aircraft would be similar to instrumentation found on drop-sondes. The boundary layer aircraft would carry an infrared pyrometer, an instrument to measure *in situ* winds (new instrument development), an instrument for surface imaging (visible), a sensor to measure turbulent fluxes (new instrument development), and other instruments commonly found on a meteorological drop-sonde.

Communication rates on the order of 300 kilobits/second are required to telemeter data in real-time. A wide-band, line-of-sight data link will be necessary to coordinate data. On-board processing of the merged sensor data may also be required. Real-time control of the instruments (at a low bandwidth) will be needed.

Mission C.1.27: Physical Oceanography, Meteorology, and Atmospheric Chemistry

Source: University of Hawaii / Department of Oceanography
During seasonal storms in the North Pacific, North Atlantic, and the Southern Ocean small scale but relatively intense exchanges of mass and energy occur between the ocean surface and the lower atmosphere. This mission would allow scientists to study these exchanges in turbulent, high energy density environments in or near storm systems and will help them understand their broader implications for larger scale phenomena such as:

- Understanding break-up or development of the thermocline and surface mixed layer during high winds.
- Understanding transition between disorganized and coherent wave patterns that transit whole ocean basins
- Understanding vertical transport of oceanic aerosols to the marine boundary layer inversion where they participate in the Earth's radiation balance by acting as cloud condensation nuclei.
- Understanding the transport of oceanic gases to the free troposphere and stratosphere where they are photo-oxidized and participate in gas-particle conversion and atmospheric processes involving heterogeneous chemistry.

The mission would require one or possibly two UAV platforms. The concept calls for a low-altitude UAV to be designed to operate from an oceanic research vessel. During the appropriate season the ship would be stationed near a cyclogenesis region. When periodic lows developed and passed near the ship, this UAV platform could deployed into the cyclogenesis region with high waves and turbulence. Since cloud cover may preclude the platform from using satellite data to autonomously track the storm system, it may be desirable to have a second UAV platform at a higher altitude to perform this function. This data could be down linked to the control station on the ship to allow an operator on the ground to re-direct the low-altitude platform's flight path. At various points in the mission it would be desirable for the low-altitude platform to deploy drop-sondes or buoys to track ocean surface features. Another feature of the mission would require the low-altitude platform to fly along- and across wind patterns for collecting thermodynamic, gas, and aerosol data. After the mission the low-altitude platform would be recovered by the ship.

To perform this mission the low-altitude UAV platform requires an endurance of 6 to 24 hours. Altitude range does not have to be great, but should cover 10 ft (3 meters) from the surface up to 19,700 ft (6000 meters). As such the vehicle management system should include terrain avoidance and should be able to operate in seas with 33 ft (10m) face-height swells. The management system should also allow flight path re-direction from the ground station. Despite the maneuvering required and the turbulence, it is desired to keep the platform at a relatively stable attitude. The platform must be rugged, capable of operating in Beaufort scale 6+ winds/sea state. An additional feature is that the platform should be waterproof, corrosion resistant, and able to withstand the likely event it crashes into the ocean. In this event a transponder and a neutrally buoyant recovery system would aid in the recovery of the vehicle. The platform should fly 2 to 3 times per week.

The payload is divided into three classes of measurements: meteorology/thermodynamic, trace gases, and aerosols/droplets. The total estimated weight is 2200 to 8800 lbs (1000 to 4000 kg), and the estimated volume is 35.3 to 141 ft^3 (1 to 4 m^3). The payload requires rear-facing trace gas sampling ports, self-aspirating aerosol sampling ports designed to reduce droplet shatter, and forward and nadir viewing imaging equipment that is self-cleaning in the presence of sea spray.

Fast, reliable communication links that allow real-time monitoring of the platform and data recording on the ground station is essential. Also, some uplink control of the low-altitude payload instrumentation is necessary.

Mission C.1.28: Tracking Long Distance Transport and Evolution of Pollution

Source: NASA Science Mission Directorate / Tropospheric Focus

The purpose of this mission is to observe over long distances, time periods, and multiple altitudes, the progression and movement of pollutants, by measuring the composition of the gases and aerosols. Part of this study is to analyze the impact of pollution on climate and chemistry. The mission will utilize inert tracers to identify plume position, reactive tracers to interpret chemical evolution, and other products to determine ozone formation, oxidizing potential, and aerosol interaction. With the long duration capability of suborbital platform, Lagrangian sampling can be achieved.

Improved targeting of atmospheric phenomenon and integration of observations from other satellites and UAVs are mission features. Once pollution has been identified, platform will follow plume while providing measurements on pollutants. Key characteristic of mission is near continuous air space access at all locations and altitudes.

The platform must provide a long range (> 5400 nm or 10000 km), long duration, (10 – 15 days), and various flight altitudes (0-50000 ft or 0 - 15.2 km), depending on its role as a remote sensing vehicle or an *in situ* vehicle. The vehicle should be able to be targeted globally and endure all seasons.

Payload instrumentation needed for this mission includes inert tracers and reactive tracers. For a remote sensing platform, the sensor suite would consist of approximately seven instruments, totaling 1600 lbs (726 kg) in weight and 100 ft^3 (2.8 m^3) in volume. The power involved in this setup is 10 kW. The *in situ* measurements involve 21 instruments, with an overall weight of 2500 lbs. (1134 kg) and volume of 150 ft^3 (4.3 m^3)

Real-time communication for re-directing aircraft in mid-air to ensure that platform is within pollution plume. In addition, OTH communications for real-time control is crucial to perform any necessary corrective action.

Mission C.1.29: Cloud Systems- Clouds/ Aerosol/ Gas/ Radiation Interactions

Source: NASA Science Mission Directorate / Tropospheric Focus
This mission will perform in-depth analysis of cloud microphysics, chemistry and optical properties during formation, evolution, precipitation and dissipation. Clouds are the chemical processing factory of the atmosphere, affecting the hydrologic cycle and the radiative balance of the planet. The results of this project will help to:

- establish the link between the clouds, hydrologic cycle, radiative balance of the planet, weather, aerosol geochemical cycles, and other cycles
- provide better understanding of natural and anthropogenic aerosol/gas constituents upon cloud properties.

Currently, airborne platforms have a difficult time sampling data of cloud cycles on scales of minutes and hours to days. With the ability to linger and fly extended missions in cloud environments, suborbital UAV platforms can observe the condensation, activation, and evolution of the aerosol and cloud droplet spectra and their effect on the precipitation, lifetime, and optical properties of the cloud. This mission also includes the possibility of coordination with other platforms to combine data when concurrent measurements are made. In this situation, the in-situ aircraft characterizes cloud droplet evolution over cloud lifetime. Another aircraft measures aerosol properties, and visible and IR fluxes below the clouds, while a third aircraft flies above the cloud system, measuring visible and IR fluxes.

This mission places the following requirements on the platform. The platform must have an endurance of 1 hour to 2 days. The platform will be flying at altitudes between 1600 ft (0.5 km) and 98,000 ft (30 km). In addition, with the platform experiencing different conditions within the clouds, the aircraft must be robust and watertight with anti-icing capabilities. The platform will also have the capability for drop sonde deployment.

The instrument/payload characteristics involved in this mission measure or monitor:

- aerosol size distribution
- light scattering
- light absorption
- cloud droplet distributions
- droplet chemistry
- short wave and long wave radiative fluxes

- precipitation chemistry
- imagery

Some environmental variables to be measure are humidity, temperature, pressure, dew point, ice point, trace gases and ionic species.

Real-time satellite communications are required for platform and instrument control. If utilized the mission also requires local radio communication with drop sonde receiver.

Mission C.1.30: Long Time Scale Vertical Profiling of Atmosphere

Source: NASA Science Mission Directorate / Tropospheric Focus
This mission was envisioned for observing and making measurements of high resolution vertical chemical structure of the atmosphere. Once these measurements are combined with ground based and satellite measurements, a map showing the vertical structural composition can be generated. Such a mission can be included within the atmospheric composition sector of Earth Science Enterprise focus.

The concept for this mission requires multiple platforms. Initially, a high altitude platform aircraft flies to a specific site of interest. Upon reaching maximum altitude at the location, the aircraft begins real-time data transmission and updated positional information leading to the takeoff of the low altitude platform. As the high altitude aircraft flies in a downward spiral and the low altitude aircraft in an upward spiral, they can coordinate with each other and begin profiling. With the capability of loitering at a location, the platforms can provide critical validation data for ground based and new satellite systems capable of tropospheric profiling.

The requirements of this mission include the ability of two platforms to fly in a coordinated manner in the same vertical column with only a 5,000 ft (1.5 km) overlap. Both aircrafts can make combined measurements from ground level to 60,000 ft (18.2 km) above ground level (AGL) while maintaining latitude and longitude for the entire vertical profile. The platforms need to complete the vertical profile in approximately 20 minutes. In addition, the platforms must be able to change altitude rapidly to insure accurate mapping of the vertical column. Other platform characteristics include duration for multiple vertical profiles, coordinated platforms with real-time command capability, and heavy lift.

Payload instrumentation for this mission is fairly extensive, including sensors that take measurements of hydrocarbons, ozone, nitrogen oxides, aerosols, radiation (UV-VIS and IR), and tracers, such as CO, CH_4, and N_2O. The total payload weighs 1500 lbs (680.4 kg) and requires 3-4 kW power. Additionally, free air stream sampling for reactive species and unimpeded field of view zenith and nadir for radiation are needed to accomplish this mission.

Real-time communication is needed for multi-platform coordination within a vertical space and positional data to insure single point profile.

Mission C.1.31: Global 3D Continuous Measurement of Environmentally Important Species for Assimilation in Global Models

Source: NASA Science Mission Directorate / Tropospheric Focus
The purpose of this mission is to collect three-dimensional (3D) continuous measurements for environmentally important species for assimilation in global models. Specifically, this mission would measure:

- global evolution of atmospheric composition on time scales from synoptic to decadal
- regional emission and continental outflow
- resolution of fine vertical structures inaccessible from satellite observations

With these observations, improved emission estimates, more accurate global trends, and better model descriptions of processes can be made and continuous monitoring of plumes is possible. Areas impacted by these observations consist of numerical weather prediction, carbon cycle science, and climate variability.

This mission requires a fleet of approximately 1000 platforms, potentially including balloons and UAVs, all globally deployed. With each platform making daily vertical profiles, this enables a continuous observation from the surface to 65,600 ft (20 km) altitude which is not prohibited by a cloudy environment.

Instrumentation for this mission will measure key species controlling Tropospheric ozone, aerosols, and greenhouse gases. Remote payload includes ozone/aerosol/water lidar, drop sonde, and differential optical absorption spectroscopy.

Communication requirements were not addressed for this mission.

Mission C.1.32: Transport and Chemical Evolution in the Troposphere

Source: NASA Science Mission Directorate / Tropospheric Focus
This suborbital mission would help scientists improve process-based understanding to guide chemical transport models and knowledge of global-scale transport. Critical observations will be gathered on processes of transport and chemical evolution in the troposphere, such as intercontinental transport of plumes, convective processing, and lightning effects. Specifically, the mission must provide science data on chemical evolution and movement in scales ranging from convective to global. Information will also be collected on ozone, aerosols, and related species affecting their evolution.

These observations and measurements will support the tropospheric science focus. Areas impacted by this mission include numerical weather prediction, biogeochemical cycling, and climate dynamics.

This mission requires the use of a “Mothership” and several drone UAV platforms. The mothership will initially perform remote sensing. In doing so, it characterizes the spatial extent of the air mass being probed and commands the information to the drone UAVs in real-time, allowing for continuous flight adjustments. The drone UAVs will fly above and below the mothership along patterns directed by the mothership.

In the performance of this mission, both mothership and drone units must fly between the surface and 65,600 ft (20 km). As such, vehicle management systems should employ terrain avoidance. All platforms are required to have an endurance of one week and a range of 8100 nm (15,000 km). In addition, balloons will be used to perform Lagrangian sampling.

The payload of the mothership includes extensive remote instrumentation. The drone UAVs, however, will have mostly in situ instrumentation. The in situ payload consists of sensors for ozone, aerosols, precursors, related radicals, greenhouse gases, and tracers with spectrum of atmospheric lifetimes. The remote payload incorporates ozone/aerosol/water lidar, Differential Optical Absorption Spectrometer, drop sondes, Fourier Transform Spectrometer, and wind profiler. A key issue to consider with the instrumentation is care in avoiding contamination from UAV exhaust.

Since optimal mission achievement requires in-flight re-tasking in near-real-time, OTH communications capabilities is essential. This re-tasking of the drone units occur in mid-flight as the mothership updates new information on the air mass being monitored.

C.2 Land Management Missions

Mission C.2.1: Wildlife Management Population Count

Source: Land Management and Coastal Zone Dynamics Workshop / Wildlife Focus Area

The goal of this mission is to collect data for population counts of wildlife species to enable effective management of the population of that species. The species of interest ranges from birds, to herds of wild horses or burros, to bears, who operate independently.

The mission requires 2 platforms, one as surveyor to locate herds or individual members of a targeted species within a specified area, or on a linear path along a seacoast, and the second as a tracker to perform detailed population counts and habitat observations of the targeted species. The surveyor vehicle flies within a pre-designated target area or path searching for the species of interest. Members of the species are located and identified autonomously. The location of an identified species is transmitted to the tracker vehicle, which autonomously tracks the animal, or animals, to identify age, sex, and the number. This mission is envisioned to be seasonally driven, once a year, and include missions in Alaska where night time operations are required.

The surveyor platform must cover a targeted area of 10,000 square miles (34,300 square km), set by requirements for operations in Alaska. Smaller areas of coverage, 1000 square miles (3430 square km), are required in the lower 48 states. Linear searches along a seacoast of 700 – 1000 miles (1300 – 1850 km) may be required. Speed requirements are established for optimum identification and tracking performance, based primarily on sensor precision and accuracy and detection algorithm accuracy. Platform endurance requirements, established on speed and size of the targeted coverage area, are not specifically identified, but are estimated between 8 - 16 hours. The altitude of the surveyor platform would be established based on the species of interest. For birds the platform would operate near the surface, requiring the vehicle management system to include terrain following and collision avoidance. For other species an altitude of 10,000 feet (3 km) would be sufficient. The vehicle management system must be able to accept re-tasking commands from a ground operator, or scientist, monitoring the flight. The tracker platform has similar requirements as the surveyor. Its vehicle management system must accept tasking commands from the surveyor vehicle, as well as a ground operator, or scientist. Once the tracker has been given a tasking command, the vehicle management system must be able to autonomously home and track the animals.

It is desired for both platforms to operate quietly at low altitudes, as high frequency propulsion noise can have negative influence on animal behavior, especially the aviary population.

The sensor payload on both platforms is the same: an optical and IR camera. The cameras must be mounted on a gimbaled system which receives remote commands from a scientist on the ground or autonomously once a member of a targeted species is identified. The gimbaled system should allow for typical crosswinds, gusts, and down-drafts in mountain regions. The camera mounting must be isolated to reduce vibration and turbulence effects. The field of view must be variable from 1 – 120 deg, depending on the targeted species of interest, with an ability to zoom. The cameras must operate in temperatures ranging from -50 to 100 deg Fahrenheit (-45 deg – 38 deg Celsius). GPS corrected coordinates must be obtained based on camera angle and range to a target of interest. The camera accuracy and precision must allow identification of features for determining age and sex. Total sensor weight, including the gimbaled system, is anticipated to be around 25 lbs (11.3 kg).

For both platforms real-time camera data across OTH communication links are required. In addition corrected GPS location of species members of interest is required, not only for the scientist at a ground station, but for the tracker UAV as well. The ability to transmit C^2 commands for the platforms, and the gimbaled camera system, are also necessary.

Mission C.2.2: Wildlife Management Telemetry Mission

Source: Land Management and Coastal Zone Dynamics Workshop / Wildlife Focus Area

The goal of this mission is to identify the location of animals with pre-tagged radio frequency (RF) transmitters to enable effective management of species population.

The mission calls for the platform to search for a series of RF transmitter frequencies (about 50 – 75), which were previously tagged to various animals. The platform begins the mission by searching within a pre-designated target area at a medium altitude for any of the pre-loaded target frequencies. When a frequency is identified, the platform autonomously homes in on the frequency, while descending to a lower altitude, to identify the location of the animal to within about 160 ft (50 m) in open terrain, and 650 ft (200m) in rough terrain. After a successful identification the platform returns to the search pattern until all the frequencies are identified. This mission would be repeated daily, weekly, or monthly depending on the species of animals being identified, with a requirement for night operations, especially when conducting the mission in Alaska. Optical imagery of the terrain where animals are identified would be useful, but not required.

The platform must cover a targeted area of 10,000 square miles (34,300 square km), set by requirements for operations in Alaska. Smaller areas of coverage, 1000 square miles (3430 square km), are required in the lower 48 states. Platform endurance requirements, established on speed and the size of the targeted coverage area, could potentially be on the order of multi-day. The altitude requirement of the platform would be 14,000 ft (4.3 km) during the search mode, but would require descent down to 200 ft (61 m) AGL during the homing mode. Since the mission may be conducted in mountainous regions, the vehicle management system must include terrain following as well as collision avoidance. If optical imagery capability is included, the ability of the platform to dwell over a herd of animals would be useful for the purpose of population counting. The vehicle management system must be able to accept re-tasking commands from a ground operator, or scientist, monitoring the flight, to allow for repeat runs. The platform must also operate quietly at low altitudes, as high frequency propulsion noise can have negative influence on animal behavior, especially the aviary population.

The sensor payload on the platform is an omnidirectional, RF receiver. Total payload weight and power requirements are not anticipated to be large, perhaps < 10 lbs (4.5 kg) and 12 Volts respectively. Adding a simple optical camera would add a few additional pounds.

Real-time coordinate locations, identification frequencies, and optical camera imagery (if included on the platform) are required downlinks. OTH communication is required for both downlink and uplink capability.

Mission C.2.3: Wildlife Habitat Change Mission

Source: Land Management and Coastal Zone Dynamics Workshop / Wildlife
The objective of this mission is to document, with more spatial and temporal completeness than is currently available, the change in the habitat environment of various species of animals. This knowledge would enhance dynamic decision support systems designed to facilitate adaptive management policies.

The mission calls for 2 platforms: a mapping platform and an in-situ platform. The role of the mapping platform is to document changes in the land cover where a species of interest lives. Fragmentation observations from the mapping platform include plant distribution in terms of biomass and species composition, water distribution, water depth, water area, and water quality in terms of color producing agents, and anthropogenic changes in land use. The mapping platform would fly a pre-defined search pattern over a targeted area making observations of these properties with measurement accuracies of less than a meter for micro-habitat areas, and 6.6 – 16.4 ft (2 – 5 m) for macro-habitat areas. Missions would be conducted at a high frequency during the appropriate season for temporal documentation. However, extreme events, such as snow storms, or heavy rainfall would also trigger the mission, but would require some dwell time for temporal variation. For Alaska the ability to fly winter operations, which also encompasses night operations, would be desirable. A unique capability desired in the Alaska operation is the ability to measure permafrost depth to a resolution of centimeters.

After analyzing data from the mapping platform mission, specific areas of interest are identified where in-situ measurements are desired. The in-situ platform launches and lands at or hovers over these pre-designated locations taking measurements. These measurements consist of turbidity, levels of dissolved oxygen, potential of hydrogen (pH), conductivity, and levels of contaminants such as petroleum, mercury, or other heavy metals.

The mapping platform must cover a targeted area of 10,000 square miles (34,300 square km), set by requirements for operations in Alaska. Smaller areas of coverage, 1000 square miles (3430 square km), are required in the lower 48 states. However, these areas do not need to be covered in one sortie. Anticipated endurance for a given mission is 8 – 12 hours, unless an extreme event has occurred. The altitude for these missions range between 0 to 10,000 feet (3 km). The vehicle management system will require the ability to be re-tasked from a ground operator, or scientist, and should have some collision avoidance or terrain following capability. The in-situ platform will have similar requirements, with the addition that it must be able to remotely land on soil, water, or tundra; depending on the targeted location, or be able to hover and extend a probe in order to perform the in-situ analysis. A quick real-time, on-board analysis will allow the scientist monitoring the flight to re-task the vehicle for additional samples if necessary. Quiet operation is desired for both vehicles when flying at low altitudes.

The sensor payload on the mapping platform, with applications for both and water use, consists of a multi-spectral optical camera (hyper-spectral would be ideal), SAR, and LIDAR. Estimated payload characteristics are 500 – 1000 lbs (227 – 454 kg) weight, and 5 kW of power required. The in-situ payload weight is estimated to be 5 lbs (2.3 kg).

For the nominal mission for both platforms the bulk of the data can be stored on-board and analyzed post-flight. The ability to re-task requires OTH communication links for uplink commands. Quick look status data is a required downlink for the in-situ platform and requires OTH communication. In the extreme weather scenario, the mapping platform will need to downlink all data, putting more demands on the bandwidth of the communication link.

Mission C.2.4: Precision Agriculture

Source: Land Management and Coastal Zone Dynamics Workshop / Land Management Focus Area

The goal of this mission is to collect data which enhances crop productivity and resource efficiency. Observations of crop status, surface temperature, canopy, and soil moisture are critical for this mission. Weed and pest infiltration monitoring is also desired.

The mission calls for operations out of a local airstrip. Pre-defined grid patterns are flown over a select number of fields at altitudes lower than 5000 feet (1.5 km). Very few real-time adjustments to the flight profile are necessary, with the possible exception of frost monitoring. Based on the season, the frequency of this mission is as high as once or twice a day. Sun angle constraints may require the mission be centered around solar noon. Cost effectiveness is a key motivator for the mission.

The platform operates between altitudes of 500 – 5,000 ft (.15 – 1.5 km) AGL. Terrain following and collision avoidance capability are required in the vehicle management system. Platform endurance is anticipated to be 8 hours or less.

The sensor payload consists of a hyper-spectral imager, a thermal imager, a digital camera, all requiring a nadir view; a vegetation canopy or fluorescence LIDAR, a GPS/Inertial Navigation System (INS), and a video camera. Resolution requirements for the hyper-spectral imager, the thermal imager, and the digital camera are respectively, 6.6 – 9.8 ft (2 -3 m), .40 - .47 in (10 – 12 mm), and 2 in (5 cm). Power requirements for this sensor package are estimated to be less than 30 Watts, excluding the LIDAR. The following table shows current weight and volume characteristics for this sensor package, as well as future desires for these characteristics:

	Current		Future	
Sensor	**Weight, lbs (kg)**	**Volume, ft^3 (m^3)**	**Weight, lbs (kg)**	**Volume, ft^3 (m^3)**
Hyper-spectral imager	15.4 (7)	1 (.029)	4.4 (2)	.1 (.0029)
Thermal imager	2.2 (1)	.5 (.014)	1.1 (.5)	.2 (.0058)
Digital camera	1.1 (.5)	.1 (.0029)	.22 (.1)	.05 (.0014)
LIDAR	88 (40)	5 (.14)	22 (10)	1 (.029)
GPS / INS	1.1 (.5)	.1 (.0029)	N/A	N/A

The primary data is collected and stored on-board. Line of sight (LOS) communication link is required for video feed.

Mission C.2.5: Water Reservoir Management

Source: Land Management and Coastal Zone Dynamics Workshop / Land Management Focus Area

The goal of this mission is to promote sustainable use of water resources located in regions of inaccessible terrain or which are prohibited by other means, such as scale. To support the mission, observations or measurements of the chemical composition (in-situ sampling), temperature, surface area, and depth of the water resource are necessary. Time critical measurements of sediment, soil moisture, and algae content are required. In addition satellite calibration and validation of snow pack characteristics are also desired.

This mission requires one platform to perform periodic schedule driven missions on a seasonal basis to document baseline characteristics. Features of interest include rivers, lakes, snow packs, soil moisture, sub-surface water, ice melts, and watersheds. During event driven phenomena, such as storms or floods, daily operations are desired for the purpose of documenting pre- and post storm assessments. Depending on the sensor payload, sun angle constraints may apply.

For scheduled driven missions the platform must provide coverage for a large region or a state. Endurance requirement is estimated to be 8 hours, with operations occurring between altitudes of 5,000 – 20,000 ft (1.5 – 6.0 km). Very little re-tasking of the vehicle management system is anticipated with this mission.

The sensor payload consists of a hyper-spectral sensor with 16.4 – 65.6 ft (5 – 20 m) resolution, a thermal imager, and a digital camera. Resolution requirements for the thermal imager and the digital camera are respectively, .40 - .47 in (10 – 12 mm), and 2 in (5 cm). For obtaining snow pack depth a LIDAR could be included or else an active and passive microwave system for measuring snow / water equivalent and for flood mapping.

The primary data is collected and stored on-board. LOS communication link is required for video feed.

Mission C.2.6: Range Management

Source: Land Management and Coastal Zone Dynamics Workshop / Land Management Focus Area

The objective of this mission is to assess and improve range land management. Broad coverage observations of vegetation species and their condition, biomass, and soil moisture are specific goals for the mission. Identification of spatial and temporal patterns and gaps are desired. This data can be used for state and transition, and ecosystem modeling, and supports land management policy decision making.

The mission calls for a platform, probably a MAV, to be launched from a ground vehicle near a large region of interest. The platform flies a pre-programmed flight pattern and then returns to land, on relatively rough terrain, near the launch vehicle. The ground vehicle transports the platform to a new location, and the mission repeated. Due to remote area operations, a short take-off and landing (STOL) vehicle is envisioned for this mission. During key seasons, daily operations are anticipated, but event driven operations are also desired.

The platform must operate between altitudes of 250– 5,000 feet (.076 – 1.5 km). As such the vehicle management system provide terrain following and collision avoidance. In addition the vehicle management system must be able to identify potential landing spots, select a landing spot, and execute the landing. Large transects over the regions of interest are anticipated, implying significant range capability in the platform. The endurance requirement for the platform is established at 8 hours.

The sensor payload on the platform consists of a multi-spectral imager, 4 bands, with 3.28 ft (1 m) resolution; a thermal imager, a digital camera, a GPS/INS, and a video camera. Resolution requirements for the thermal imager and the digital camera are respectively, .40 - .47 in (10 – 12 mm), and 2 in (5 cm). A LIDAR is optional. Except for the LIDAR, the power requirements for the sensor payload package are estimated to be 30 W or less. The following table shows current weight and volume characteristics for this sensor package, as well as future desires for these characteristics:

Sensor	Current Weight, lbs (kg)	Current Volume, ft^3 (m^3)	Future Weight, lbs (kg)	Future Volume, ft^3 (m^3)
Multi-spectral imager	11 (5)	.5 (.014)	4.4 (2)	.1 (.0029)
Thermal imager	2.2 (1)	.5 (.014)	1.1 (.5)	.2 (.0058)
Digital camera	1.1 (.5)	.1 (.0029)	.22 (.1)	.05 (.0014)
LIDAR	88 (40)	5 (.14)	22 (10)	1 (.029)
GPS / INS	1.1 (.5)	.1 (.0029)	N/A	N/A

The primary data is collected and stored on-board. LOS communication link is required for video feed.

Mission C.2.7: Urban Management

Source: Land Management and Coastal Zone Dynamics Workshop / Land Management Focus Area

The goal for this mission is to provide small governments effective tools for land management. As urban regions expand, wildlife, range land, forest, and coastal regions are affected. In addition, storm run-off can be modified creating localized flooding in certain areas. Effects of heat islands can also be examined. A UAV provides an effective tool to help manage these effects by measuring or observing land usage, pavement quality and coverage, population density, and changes in topography. This data supports urban hydrology models, development plans, and traffic monitoring.

The mission calls for a platform, probably a MAV, to be launched in or near the urban area. The platform flies a pre-programmed flight pattern and then returns to land, on relatively rough terrain, near the launch site. Due to urban area operations, a vertical take-off and landing (VTOL) vehicle is envisioned for this mission. Normal operations, including night operations, occur monthly or annually. But supporting event driven, daily operations are anticipated.

The platform must operate between altitudes of 250 – 5,000 feet (.076 – 1.5 km) in the vicinity of people and buildings. As such the vehicle management system provide terrain following and collision avoidance, and adhere to strict flight safety requirements. The endurance requirement for the platform is 8 hours.

The sensor payload on the platform consists of a multi-spectral imager, 4 bands, with 1 m resolution; a thermal imager, a digital camera, a GPS/INS, and a video camera. Resolution requirements for the thermal imager and the digital camera are respectively, .40 - .47 in (10 – 12 mm), and 2 in (5 cm). A LIDAR is optional. Except for the LIDAR, the power requirements for the sensor payload package are estimated to be 30 W or less. The following table shows current weight and volume characteristics for this sensor package, as well as future desires for these characteristics:

	Current		Future	
Sensor	**Weight, lbs (kg)**	**Volume, ft^3 (m^3)**	**Weight, lbs (kg)**	**Volume, ft^3 (m^3)**
Multi-spectral imager	11 (5)	.5 (.014)	4.4 (2)	.1 (.0029)
Thermal imager	2.2 (1)	.5 (.014)	1.1 (.5)	.2 (.0058)
Digital camera	1.1 (.5)	.1 (.0029)	.22 (.1)	.05 (.0014)
LIDAR	88 (40)	5 (.14)	22 (10)	1 (.029)
GPS / INS	1.1 (.5)	.1 (.0029)	N/A	N/A

The primary data is collected and stored on-board. LOS communication link is required for video feed.

Mission C.2.8: High Resolution Sampling of Coastal Water Quality

Source: Land Management and Coastal Zone Dynamics Workshop / Ocean and Coastal Region Focus Area

The purpose of this mission is to perform high resolution sampling of coastal water quality. After a storm occurs, storm water discharge is often laden with oils and agricultural sediment. Currently, it is not possible to monitor coastal water qualities on a regular basis due to cloud cover. Information on plumes, such as their boundaries, shape, size, direction of propagation, and persistence are highly desired. Other phenomena of interest include Harmful Algal Blooms (HAB), and color dissolved organic matter (CDOM). Observations required to support the mission are sea state reflectance, temperature, sea state roughness, fluorescence, imagery, and water quality samples.

It is envisioned that a UAV platform will be deployed after storms have passed through the local area or based on readings from ocean buoys. Once the plume is identified from a higher altitude (at 16.4 – 984 ft or 5 – 300 m resolution), the platform descends to lower altitudes below cloud levels to obtain higher resolution data. The plume is mapped to within 6.6 – 16.4 ft (2 – 5 m) resolution, and then subsequently tracked. In addition, on-board data processing of the data is necessary, so that, if required, results can be transmitted to the appropriate entities. One potential benefactor of this data would be beach life guards. When un-safe water conditions occur, they could take appropriate measures, such as closing beaches to protect the general public. Measurements from this mission may require coordination with shore station measurements.

The platform shall fly at low to moderate speeds, have a range of at least 300 nm (555 km), and endurance ranging from 12 hours to 3 days. The platform shall fly at 30,000 ft (9 km). to obtain the domain picture perspective, lowering to 3000 ft (.9 km) or less, below cloud levels, to obtain the necessary resolution. The vehicle management system shall support either operator in-flight re-tasking, or a high level of autonomous payload directed flight, or both.
C or L Band SAR will be used to detect and measure the storm water discharge plumes. Multi-spectral sensors will measure water properties such as nutrients, chlorophyll, and CDOM. Hyper-spectral, visible, and infra-red imagery will be used to detect and measure HAB. The SAR weighs approximately 22 – 44 lbs (10-20 kg), has a 4.4 ft^3 (0.125 m^3) footprint, and draws 1-2 KW. Hyper-spectral and multi-spectral sensors

weigh approximately 22 lbs (10 kg) have a 1 ft^3 (.029 m^3) footprint, and draw 20-30 Watts of power.

The platform will require an OTH communication link to support network centric operations, and a data Link for health/status monitoring (a high bandwidth capability would be an asset). Envisioned data rates are on the order of 1 Megabyte – 1 Gigabyte per sec for the spectral sensors. Due to its size, SAR data will be stored on board the vehicle.

Mission C.2.9: Identification and Tracking of Maritime Species

Source: Land Management and Coastal Zone Dynamics Workshop / Ocean and Coastal Region Focus Area

The purpose of this mission is to locate and track endangered maritime species. For purposes of discussion, the endangered species will be tuna, and the setting is the central/northern Atlantic Ocean. The European species of tuna is currently endangered due to over-fishing. Several fish in a school are tagged to identify their movement and position. However, these markers are visible only when the fish are near the surface of the water. Tuna are visible and relatively stationary when they are feeding. They feed for a few hours, 2-3 times a day, and then dive into deeper water where they are undetectable. In addition to population counts and migration tracking, habitat quality is evaluated in this mission.

It is envisioned that this mission is cued by satellite observation of tagged tuna to identify feeding area locations. A UAV platform will be deployed to search for the tuna, and once identified, loiter over the feeding area to make observations. As the tuna migrate, the platform will autonomously track them. Also envisioned in this mission is the capability for the platform to be able to identify potential fishing vessels by making observations at lower altitudes. The mission ranges from close to shore to the middle of the ocean anytime of the year.

The platform shall have viewing and sampling ports as required. In addition, it shall have all weather capability, a high dash speed to get on-condition quickly, and endurance on the order of several days (2 -3, but the longer the better). A range of 3000 nm (5600 km) and a loitering speed of 50 knots (93 km/hr) are desirable. Specific platform altitude requirements are a function of the sensor payload, but are estimated at 30,000 ft (9 km) while searching and tracking tuna, and 10,000 ft (3 km) when identifying fishing vessels.

The platform shall employ standard interfaces to facilitate payload installation and removal. Payload shall consist of a long wave infra-red camera, a video camera, and Lidar. Lidar would be used to find the tuna. Desired performance includes 3.28 ft (1 m) resolution from 30,000 ft. (9 km) with a 30 degree look down field of view. The long wave infra red camera system weighs about 33 lbs (15 kg) and draws 20-30 watts of power. The video camera system weighs about 11 lbs (5 kg) and draws about 20-30 watts of power. The Lidar weighs about 4.4 – 22 lbs (2-10 kg) and draws about 5-40 watts of power.

The platform will require OTH communication link(s) to support network centric operations, and a data link for health/status monitoring (a high bandwidth capability would be an asset). Photographs of fish will be transmitted to appropriate parties for identification purposes.

Mission C.2.10: Shallow Water Benthic Ecosystem

Source: Land Management and Coastal Zone Dynamics Workshop / Ocean and Coastal Region Focus Area

The purpose of this mission is to monitor changes in the shallow water benthic eco-system. An example mission would take place at Kure Atoll, in the Northern Pacific Ocean. Kure Atoll is located approximately 1200 nm (2200 km) from Hawaii. Observations of reflectance, SST, currents, salinity and PH of the water, and rugosity are required to support the mission.

Based on coral reef bleaching alerts from buoys and/or satellites, the UAV platform would be launched from an airstrip on Midway Island, 49 nm (90 km) from south-east from Kure Atoll, or from a ship. From its launch point, it would travel to Kure Atoll, the northernmost coral atoll in the world. Due to its northern latitude, this atoll is very sensitive to climate change. There is a 4 hour window from 10 AM – 2 PM, that is critical for measurement purposes. The platform will fly at a high enough altitude to obtain coverage of the entire reef, descending to low altitude to obtain high resolution imager of sites of interest. These measurements may require coordination with a team of divers taking in-situ measurements as well. Once measurements are complete, the mission is repeated, regularly, perhaps annually, to detect changes.

The platform shall be transportable via ship. In addition, the platform shall launch from a ship as well as land-based runways. The platform shall incorporate viewing and sampling ports as required. Desired attributes include a 50 knot (93 km/hr) loitering speed, 200 nm (370 km) range, and a 6 hour endurance. The platform shall fly between 10,000 and 20,000 feet (3 – 6 km) for reef coverage, and at 1000 ft (300 m) for better resolution data. To accurately detect change over a period of time, the mission requires repeatable ground-track passes. Hence, the platform vehicle management system needs to have very precise navigation capability, and support in-flight re-tasking by an operator. The platform shall be recovered via land-based runway or by ship, the latter either by flight into a net or splash down into the ocean.

Payload shall consist of a hyper-spectral sensor, lidar, and a high-resolution digital camera. The hyper-spectral sensor system weighs 22 lbs (10 kg) and draws 20-30 watts. The lidar weighs between 4.4 – 22 lbs (2-10 kg) and draws 5-40 watts. The high resolution digital camera weighs 11 lbs (5 kg) and draws 5-10 watts. Desired digital camera performance consists of < 3.28 ft (1 m) per pixel resolution at an altitude of 1000 ft (300 m) or less and 16.4 – 32.8 ft (5 – 10 m) per pixel during the reef coverage portion of the flight.

Communication requirements are relaxed, as a result of the non-real-time nature of the data collected. The platform system will perform on-board data recording which will be available upon returning to base. OTH data links for uplink commands and health/status are required.

Mission C.2.11: Carbon Dioxide Flux

Source: Land Management and Coastal Zone Dynamics Workshop / Ocean and Coastal Region Focus Area

The primary purpose of this mission is to correlate atmospheric turbulence with carbon dioxide flux. Ancillary phenomena of interest include primary productability (5 m resolution), CDOM (16.4 ft or 5 m resolution), sea-state (6.56 ft or 2 m resolution), and winds.

The UAV platform shall launch from either New Zealand or South America and fly to the Southern Ocean. Once on station, it will descend to an altitude less than 82 ft (25 m) AGL, and loiter for 8-24 hours while collecting measurements. When carbon dioxide flux is measured, the feature of interest is vertically mapped, documented, and tracked. In this scenario real-time processing of imagery to identify chlorophyll is required to allow autonomous tracking. Once measurements are complete, the mission is repeated on a yearly basis to detect changes.

The platform shall incorporate viewing and sampling ports as required. Desired attributes include a 150 knot (280 km/hr) (dash speed (this speed is limited by the in-situ sampler), a range of at least 3000 nm (5500 km), endurance of 2-3 days, and an operational altitude of about 32.8 ft (10 m) AGL. The vehicle management system must provide collision avoidance, in particular for large waves. The platform vehicle management system needs to provide high precision navigation measurements for estimating winds, and the ability of an operator to re-task in-flight.

Payload consists of a very high fidelity nine hole air data probe, a laser/radar altimeter, a gas chromatographer, forward looking radar/laser, and multi-spectral sensors. The nine-hole air data probe is required for turbulence or relative air velocity measurements, weighs 8.8 lbs (4 kg), and requires 2 watts of power. The forward looking laser/radar altimeter is used to determine sea surface height. It weighs 11 lbs (5 kg) and requires 2-3 watts of power. The gas chromatographer shall sample at greater than 30 Hz along the flight track. It weighs 22 lbs (10 kg), occupies approximately 1 cubic foot (.029 m^3) and requires 2-3 watts of power. The forward looking radar/laser weighs 11 lbs (5 kg) and requires 10 watts of power. The multi-spectral sensor weighs 11 lbs (5 kg) and requires 20-30 watts of power.

The platform will require OTH communication link(s) to support network centric operations, and a data link for health/status monitoring (a high bandwidth capability would be an asset).

Mission C.2.12: Wildfire/Disaster – Real-time Communication

Source: Land Management and Coastal Zone Dynamics Workshop / Wildfire Focus Area

This mission provides a UAV-based voice and RF communications relay between the field command center and personnel in the field fighting the fire or dealing with the natural disaster. Standard line-of-sight communication methods can be rendered inoperative during disaster events; such is the case with Fire fighting, for example, with typically takes place in rugged and mountainous terrain. Such a capability will significantly enhance on-scene C^2 and could provide life-saving communication to first responders.

In addition to good coverage, communication-related needs during a disaster event may also encompass such things as:

- Asset tracking (people, vehicles, and equipment), and
- Real-time airborne photo imagery, and video streaming of the event

For the communication-relay mission requirement, the UAV will have to loiter over the disaster area and maintain line-of-sight between first responders and the field command center. One larger UAV could be used at medium to high altitude to provide this capability. For the asset tracking or imagery requirements, either the high altitude UAV could be used, or multiple MAVs could be used at lower altitudes. Platforms in the low to medium altitude range require either awareness of plume location to avoid engine-out issues or propulsion with the ability to operate in dense smoke for extended periods. The aircraft would fly a racetrack pattern autonomously for extended periods unless the mission is replanned due to changing circumstances. The vehicle should have a vehicle health monitoring capability.

Payload capability would encompass RF and cellular (and text) relay equipment, and video and imagery equipment that would weight approximately 100 – 150 lbs (45.4 – 68 kg).

Video streaming and imagery data would be communicated at a rate of 64 to 500 kbs. Standard RF relay equipment would be used for the RF and cellular relay requirement. The vehicle would be controlled either OTH or with LOS control using low bandwidth communications. Special communication capabilities that would be desirable include encryption, and data compression to minimize requirements.

Mission C.2.13: Wildfire/Disaster – Predict, Measure, Monitor, and Manage Events

Source: Land Management and Coastal Zone Dynamics Workshop / Wildfire Focus Area

The wildfire mission (see Note below) shall provide information to the fire fighting agencies and other emergency responders on how to manage their response to the emergency. Specifically, the mission shall encompass the following activities:

- Locate fire hotspots, determine the active fire front, and identify the already burned-out areas.
- Determine the intensity of the fire and its movement and rate of spread shall be measured to help predict the near-term fire behavior.
- Determine local weather and, more specifically, the vertical temperature profile over the fire,
- Measure the fuel moisture levels shall aid in this prediction, and
- Measure the air quality in the fire plume, including particulate levels, to aid in disaster-related evacuation decisions.

These real-time measurement and monitoring activities would significantly aid fire fighting agencies by giving them the data necessary to predict near-term fire behavior and thus allow them to more effectively fight the fire and provide evacuation guidance to nearby population centers.

This mission also allows authorities to assess the level of damage to an area following a natural disaster. The ability to place long-term sensors over the area after the event would provide an opportunity to assess the extent of damage, and the changes occurring in the aftermath (such as in the alternate disaster cases other than a wildfire: fires in urban area after an Earthquake, water drainage after a tsunami, or the movement of a particulate plume after a volcanic eruption). Such observations would significantly aid emergency planners in disaster control and providing additional evacuation or return advisories to nearby population centers, as necessary.

This mission would be optimally conducted with a medium altitude long endurance (MALE) UAV platform flying at an altitude no higher than 16,000 feet (4.3 km) for accurate imaging of the fires – although a HALE vehicle, with appropriate using high fidelity sensors, could also perform this mission. It is desirable to have flight over the fire within one hour (which is preferred) to 12 hours of it first being detected; an over flight of the event should occur every one half hour after that – and it is desirable to stay on station from 4-48 hours. The UAV should have a cruise speed of approximately 150 knots (280 km/hr) and have high tolerance to turbulent conditions. Features such as autonomous flight, auto flight profile and mission replanning, and integrated vehicle health management are considered beneficial. There is an identified role for small UAVs, locally controlled, for low altitude air data sampling as discussed below.

Payload imaging sensors include VIS/IR (in the reflective and mid-IR range, 2.0-2.8 micron) and 1.75 micron IR (for fuel moisture sensing). Additional related sensors include a gas sampling sensor for in situ sampling/remote measurement of particle matters less than 2.5 microns, $NO_{2,}$ Nox, CO, and a meteorological sensor for vertical temperature and humidity profiling. This last sensor requirement may be fulfilled with small UAVs that provide real-time air temperature and humidity data with ground temperature and humidity measurements, coupled with wind conditions at 20 ft. (6.1 m), to feed the input requirements of predictive computational models.

Communication of sensor data from the UAV should be real-time to aid in management and prediction activities. MALE or HALE aircraft would be operated using OTH communication, whereas the small UAV, if used, would be remotely operated from a nearby local airfield or special fire-fighting location.

Note: A generic disaster event mission description will be very similar to this, but vary slightly depending on the nature of the disaster (such as an Earthquake, tsunami, volcanic eruption, or a wildfire).

Mission C.2.14: Wildfire – Fire Retardant Application

Source: Land Management and Coastal Zone Dynamics Workshop / Wildfire Focus Area

In recent years the US has seen the advent of Mega-Fires, driven by gradual increases in consumable fuels and the continued encroachment of civilization on our wilderness areas. These wildfires and other fire-related disasters are high-risk events for first responders and the public. This mission shall employ a specialized low-altitude UAV, to replace the role served traditionally by piloted aircraft, for the airborne application of fire retardant. Additional risk reduction is provided by removing the pilot out of harm’s way in what is a highly dangerous flight environment.

This UAV would be a substantial low-altitude UAV capable of carrying a fire retardant payload of 1000 lbs (454 kg) if it is a rotorcraft, or up to 4000 lbs (1814 kg) if it is a fixed-wing craft. It will be capable of auto-takeoff, autonomous flight, auto-landing, and be able to fly at 300 knots (560 km/hr), have a range of 500 miles (925 km), and fly at a minimum controlled altitude over the drop zone of 100. ft (30.5 m) AGL, and be able to sustain a 6-G pull-up after dropping its payload. It is suggested that the vehicle be capable of flying in a UAV “swarm” or formation. The vehicle should be capable of in-flight re-tasking and be able to operate with real-time drop-zone coordinate information provided by RF communication from other UAVs or mission control. The vehicle should be capable of being redeployed immediately after landing and being supplied with a new payload.

The payload of this vehicle shall be the fire retardant, which typically is water.

Limited RF communication is necessary, other than standard C^2 communication. LOS C^2 control should be capable of being transferred to a local disaster site manager from that of the launch and recovery site. There is no requirement for onboard imagery.

Mission C.2.15: Wildfire/Disaster – Reducing Risk to Responders and the Public

Source: Land Management and Coastal Zone Dynamics Workshop / Wildfire Focus Area

This mission shall employ a low-altitude UAV to provide risk reduction to emergency responders and the general public by performing the following tasks:

- Provide information for a rapid, local assessment of a situation by an on-scene responder.
- Provide accurate long-term information regarding the nature, location, and extent (and spreading, in the case of a wildfire) of a disaster event to aid the deployment of first responders, and to aid public safety agencies in their evacuation announcements, as necessary, to the general public.

These capabilities will significantly enhance safety and reduce risk by ensuring that the correct, accurate information – in some ways not available in any other fashion – is available to disaster-event decision makers.

This mission requires a locally deployed (preferably truck or trailer launched), relatively low-altitude, small to mid-sized UAV capable of autonomous day or night flight, and auto-landing. It would preferably have VTOL or STOL capability. It should be capable of flight to 10,000 ft (3 km) and in-flight mission re-tasking. It would be capable of flight durations of 1-8 hours persistence for loitering and “staring” capability of the event. The platform would be capable of short-term “over-the-hill” out-of-C^2 LOS communication, if necessary, to provide the necessary observations to first responders.

The UAV should have onboard high-resolution color and thermal video. At night it should have IR and forward-looking infrared capability. These sensors should all be coupled with an INS/GPS capability for geo-location of the observed event.

The vehicle should have sufficient RF broadcast capability to relay the real-time images to portable display systems on the ground. In the possible situation that RF links are temporarily lost, such as with a wildfire in rough mountainous terrain, data recording capability must be provided to store the imagery data for later transmission.

Mission C.2.16: Wildfire/Disaster – Pre-and Post Event Monitoring & Assessment

Source: Land Management and Coastal Zone Dynamics Workshop / Wildfire Focus Area

This is a data-recording mission that is designed to provide non-real-time information to researchers for predictive purposes and to disaster authorities to provide post-event damage assessments. This mission shall observe, measure, and document such things as:

- Vegetation condition – indices, growth, moisture, land cover type.
- Erosion/streams
- Invasive and exotics – presence or absence
- Fuel loading and biomass – tons/acres
- Wild land/urban interface – ingress/egress
- Climatology/trends – weather to supplement Remotely Automated Weather System
- Infrastructure/roads
- Soil conditions
- Terrain

Such observations help predict hazards, mitigate high-risk environmental conditions, help implement post-disaster recovery operations, assist scientific understanding of post-disaster environmental recovery, and help plan for mitigation.

The UAV shall be capable of 4-hours on station during “high sun” (for radio-metric conditions). The observation location could well be a significant distance from the UAV launch and recovery location so long endurance is suggested. No altitude requirement has been specified, but a MALE or HALE capability would be desired to satisfy all sensor specifications. The vehicle would be fully autonomous and capable of OTH control of course. Revisit time should be weekly for indices, monthly for post-event monitoring.

Sensor-specific information that has been specified for this mission is:

- Hyper-spectral (LIDAR or SAR) with open port and pressure vessel
- Spatial resolution required:
    - Urban areas – 16.4 ft (5 m)
    - Invasive areas – 16.4 ft (5 m)
    - Other areas – 98.4 ft (30 m)
- Spectral specifications:
    - Invasive areas – hyper-spectral to 2.3 micro-meter
    - Biomass areas – multi-spectral
    - Infrastructures – visible
- LIDAR or SAR for terrain

All data would be stored on the vehicle, so no communication other than C^2 is required.

C.3 Homeland Security Missions

Mission C.3.1: Marine Interdiction, Monitoring, Detection, Tracking

Source: Department of Homeland Security Workshop, Herndon VA, July 2005
The purpose of this mission is to monitor, detect, track, and interdict targets of interest to the DHS. When specific target intelligence is provided from other assets such as manned aircraft, buoys etc., a readily deployable UAV platform, a.k.a. surveillance system, launches from land. An automated search pattern is then initiated. If needed, the operator may re-task the platform. On board algorithms will identify potential targets such as go-fast vessels. The platform will detect the go-fast vessel, classify, and identify it. The platform then contacts headquarters to determine if the identified vessel is indeed the target vessel. If affirmative, coast guard cutters or other interdiction assets will be vectored to the target. The surveillance platform will then launch a daughter ship, a.k.a. tracking system, to autonomously track the target and provide continual updates of speed, course, and location to facilitate interception of the cutters until interdiction occurs. The daughter ship may be re-tasked as needed by the operator. Other potential daughter ship applications include providing situational awareness during hostage situations, vessel boardings, and fire/damage assessment.

The mother ship (surveillance system) platform shall have all weather capability, a cruising speed of greater than 100 knots (186 km/hr), and endurance on the order of several days. The vehicle management system shall allow re-tasking by the operator. The tracker platform shall be deployable from a mother ship UAV, and be recoverable from a Coast Guard cutter either by net or by flotation. The tracker platform vehicle management system shall also allow re-tasking by an operator, but will operate nominally by autonomous optical tracking. The tracker platform shall also have all weather capability, endurance on the order of several days, and potentially, fly autonomously to a land based airport. The tracking system UAV could be expendable based on cost-benefit ratio, especially in terms of sensors.

Both platforms shall employ standard interfaces to facilitate payload installation and removal. The payload for the surveillance platform consists of a SAR, as well as EO, IR, and signal intelligence (SIGINT) sensors. The sensors shall identify go fast vessels in transit or stationary, via heat, optical, electrical, and/or wake signatures in all sea states and weather, day or night. The optics shall identify 12, 6, and 3 inch vessel lettering. In addition, the sensors and associated algorithms shall resolve geo location accuracy to within 1 mile to determine course and speed. The radar shall be able to detect go fast vessels of 1 m radar cross section. The tracker platform payload consists of standard EO and IR sensors.

The platform will require OTH communication link to support network centric operations, and a data Link for health/status monitoring (a high bandwidth capability would be an asset).

Mission C.3.2: Tunnel Detection and Monitoring

Source: Department of Homeland Security Workshop, Herndon VA, July 2005
The purpose of this mission is to monitor the areas around the border for tunnels used for smuggling and unauthorized entry. Currently, if intelligence indicates there is a

tunnel, the military is called. Investigating the tunnel scares the smugglers away. Utilizing UAVs in this mission will allow faster response times and a more efficient investigation and interdiction process.

It is envisioned that a UAV will fly along the border mapping the terrain, including man-made features such as storm drains, and communication and electrical tunnels, to establish a baseline. This baseline will be archived on board UAVs that patrol the border. During regular patrols, UAVs will fly along the border conducting signals intelligence and comparing current measurements to the baseline via on-board processing. In addition to these regular patrols, it is assumed that the Border Patrol will receive intelligence about potential targets of opportunity from other government agencies. In these cases, border patrol assets including UAVs, when appropriate, will be tasked to investigate. If an unexpected change is detected, the UAV will contact Border Patrol personnel informing them of suspected illegal activity. Before committing other assets, collaborative evidence may be solicited from other information sources, such as satellites, ground based sensors and/or robots, and agents. A decision will be made whether to interdict, or to continue observation via UAV and/or other assets. Should interdiction occur, the UAV can archive footage of the apprehension as evidence against the border violators. It also can function as a communications node as well as an ‘eye in the sky’ to ground teams. The UAV would enhance situational awareness of the ground teams, hence safety, by alerting them to the number of smugglers, their current position and movements, whether they are armed or unarmed, and aid in the identification of individuals via facial recognition software. One scenario envisioned would be for the ground agent to request data from the loitering UAV, via handheld personal digital assistant or laptop computer. The UAV would transmit the desired information to the appropriate device(s). The UAV would also transmit information to a national intelligence database for sharing amongst various government agencies.

The UAV platform shall have viewing and sampling ports as required. In addition, it shall have all weather capability, dash speed of greater than 400 knots (744 km/hr), and endurance on the order of several days. The ability to loiter overhead undetected to persons on the ground is highly desirable. If necessary, an operator shall re task the UAV to perform other actions. The UAV platform shall fly multiple flight profiles in order to support the on-board instrument payload. Depending on the instrument payload package, profiles can vary from low altitude, low speed to medium altitudes at speeds greater than 400 knots (744 km/hr). There may also be requirements on flying specific ground tracks.

The UAV shall employ standard interfaces to facilitate payload installation and removal. The ability to interchange sensor suites on the order of minutes up to a maximum of 1 hour is highly desirable. Payload shall consist of SAR, and other candidate sensors. Candidate sensors include GPS Reflectance, Passive Microwave, and magnetic anomaly detection. The SAR would map the topography of the region from medium altitudes. Desired performance consists of mapping 65.6 ft (20 m) below the surface, with a resolution of 1.64 ft (0.5 m). Desired, if feasible, is a sensor footprint of 5 lbs (2.3 kg) weight, 20 Watts power, and 0.25 ft^3 (.007 m^3) volume. The GPS Reflection Sensor has proven effective in desert terrain and is currently used in Afghanistan to detect mountain tunnels. The sensor would operate at an altitude of 10,000 ft (3 km) AGL with a desired performance consisting of 65.6 ft (20 m) penetration below the surface. The high resolution passive microwave camera allows for effective surveillance in dust, sand, and foliage. Desired performance consists of 65.6 ft (20 m) penetration below the surface. Desired sensor footprint is 25-30 lb (11.3 – 13.6 kg) weight. The magnetometer detects anomalies in the region's magnetic field, and must operate at low altitudes, low speeds, during daylight, and at a flight path angle to the suspected tunnel path. Desired performance consists of 65.6 ft (20 m) penetration below the surface with 1.64 ft (0.5 m) accuracy and 0% false positives.

The platform will require secure OTH communication link(s) to support network centric operations, and a secure data link for health/status monitoring (a high bandwidth capability would be an asset). All communication would need to occur via secure communication links.

Mission C.3.3: Broad Area Surveillance

Source: Department of Homeland Security Workshop, Herndon VA, July 2005
The purpose of this mission is to monitor border areas between ports of entry to detect unauthorized entry by immigration and customs violators. These areas include both land and maritime/coastal borders and their associated airspace. Currently, it is not possible to detect, identify, and track 100% of border crossings. Due to the lack of 24/7 airborne border coverage, unspecified amounts of weapons, drugs, and unidentified individuals enter the United States illegally. The use of UAVs will enable the border patrol to conduct greater covert and overt surveillance of the border. In addition, they will aid ground agents by enhancing their situational awareness. Specific examples include performing vehicle/target identification, identifying friend vs. foe and high priority targets via facial recognition software, determining whether individuals are armed, and serving as a communications node.

The UAV flies along the border conducting surveillance, and gathering SIGINT. It detects cross-border activity and informs personnel at the Border Patrol Regional Command Center. An area supervisor dispatches resources and re-tasks the UAV(s), as appropriate. Once on station, the UAV serves as a communications node and identifies border violators via facial features and determines whether they are armed. The UAV prioritizes tracking based on whether border violators are armed and/or carrying hazardous materials. It continues tracking border violators through detection, identification, and apprehension activities while continuously gathering signals intelligence.

The Broad Area Surveillance UAV platform shall incorporate viewing and sampling ports as required. Desired attributes include all weather capability, multi-day endurance, and the ability to carry multiple payloads. High altitude flight is desirable as it increases platform's covertness; however the altitude requirement is a function of the sensor capability. The ability of the sensor package to "steer" the platform to a target of interest is highly desirable. It is likely that UAV will face threats such as small arms fire and/or surface to air missiles, due to their low cost and ample supply. As a result, the platform needs to utilize passive and/or active measures to neutralize these threats. Passive means may include threat evasion, and/or being damage tolerant. Active means may include utilization of radar and heat seeking missile counter measures as well as platform offensive capability.

Desired Border Patrol measurements from the broad area surveillance platform include monitoring cross-border illicit activity involving people and their methods of conveyance such as automobiles, aircraft, boats, all terrain vehicles, etc…, detecting hazardous chemical, biological, and radiation materials and associated plumes, observing surface changes, illicit materials or weapons as small as hand guns, paths in grass/dirt (either via geometric or moisture determination), and gathering signals intelligence. Cameras and other associated optic sensors shall require resolution on the order of 0.25 inches (.64 cm) or greater to resolve human facial features and biometrics, aircraft tail numbers, and vehicle license plates.

The platform will require secure OTH communication link(s) to support network centric operations, and a secure data link for health/status monitoring (a high bandwidth capability would be an asset). The use of a common data link for information sharing with selected partners is highly desirable. The ability to process data and transmit signals and/or video in or near real-time to users is highly desirable.

Mission C.3.4: BORTAC Situational Awareness

Source: Department of Homeland Security Workshop, Herndon VA, July 2005
The purpose of this mission is to enhance situational awareness of Border Patrol Tactical Team (BORTAC) agents during operations. For example, two hours prior to serving a search warrant on a known drug lord, a tactical MAV platform is hand launched by BORTAC. Its mission is to conduct reconnaissance. It observes locations and activity within the facilities such as individuals, weapons, explosives, bobby traps, and other threats such as big dogs. In real-time, this information is transmitted to BORTAC personnel and relayed to the Regional Command Center. The platform continues its observations throughout the apprehension activity, and if necessary, alerting border patrol personnel to individuals exiting the facility through alternate means.

Desired attributes of the platform include being hand launched, not requiring an airfield for recovery, a ceiling of 400 ft (122 m) AGL, and an endurance of 2-4 hours. In addition, the platform shall be reusable, robust, and able to fit inside a backpack worn by a single BORTAC agent. Other requirements include flight in all weather conditions, replenishment in the field, and quiet operation. Due to its low ceiling and proximity to natural and man-made hazards, the vehicle management system shall utilize terrain and collision avoidance methodologies. The platform shall not require excessive specialized training to operate.

Desired Border Patrol measurements from the tactical platform include optical, electro-optical, and infra-red signatures. In addition, the ability to detect sounds as low as human whispering is highly desired. The ability to process data and transmit signals and/or video in or near real-time to users is highly desirable.

The platform will require secure OTH communication link(s) to support network centric operations, and a secure data link for health/status monitoring (a high bandwidth capability would be an asset). To support this requirement another aircraft, or UAV, is likely required as a communication node. The use of a common data link for information sharing with selected partners is highly desirable. The ability to process data and transmit signals and/or video in or near real-time to users is highly desirable.

Mission C.3.5: Coastal Patrol

Source: US Coast Guard
This is a U.S. Coast Guard mission. It is a surveillance mission of maritime traffic off the shores of the USA (east & west coast, Alaska & Hawaii). Flights would launch and recover from one to three locations within 100 miles (213 km) of the coast for each of the four regions listed above. Missions would traverse our coastal waters 50 to 500 miles (106.5 to 1065 km) off shore.

Aircraft will be flown primarily at an altitude between 20,000 (6.1 km) and 50,000 feet (15.2 km) ; however, occasional descents to 2,000 feet (.61 km) will occur with potential multiple unplanned climbs and descents during any given mission. The aircraft would fly from one sea region to the next and loiter in each region for a period of time. The UAV would provide surveillance support to the cutter Commander responsible for that region during that loiter-period. As such, partial or full command and control may be passed to an operator onboard that cutter. This is a year-round mission precipitating the need for an anti-icing capability. The vehicle management system should allow for direct control or flight path re-direction from a ground station. An additional variation of this mission may include the carriage and deployment of a MAV that would be used in closer proximity to suspicious vessels. The MAV would be released at altitudes 20,000 feet (6.1 km) and above and fly to altitudes as low as 100 feet (30 m). The MAV would maneuver as directed to within 300 feet (91 m) in real-time in and around the vessel under suspicion. The MAV would either terminate its mission into the ocean or be recovered on shore.

Payloads will consist of various EO and IR sensors. Sensing requirements include the ability to read vessel name, detect ship personnel activity, determine dumping activities and detect driftnets deployed in the water.

Sensor data from the UAV and MAV must be available real-time. OTH network communications for C^2 of the UAV are required. C^2 of the MAV could be routed through the mother ship.

C.4 Commercial Missions

As mentioned earlier, the primary focus of this document is the applications and technical challenges for Civil UAVs to perform Earth Science missions. However, commercial mission applications are of importance to the civil UAV community, and the Assessment Team intends to address potential commercial UAV mission scenarios for a future version of the document.

Appendix D

UAV Capabilities

Capabilities

The following sections discuss the specific capabilities required to accomplish the potential missions gathered by the Assessment Team. For each capability, a description and a current status of that capability is given. Future editions of this document will provide a more detailed update of these statuses as they become available. Within the title of each section, a first-cut estimate of the mission need of that capability is given. If the capability supported at least half of the missions, it received a “High” rating. If it supported at least 25% of the missions, it earned a “Medium” rating. The remainder (those supporting less than 25%) were rated “Low”. It should be noted that mission need does not imply mission priority. The key capabilities are depicted in Figure D.1.

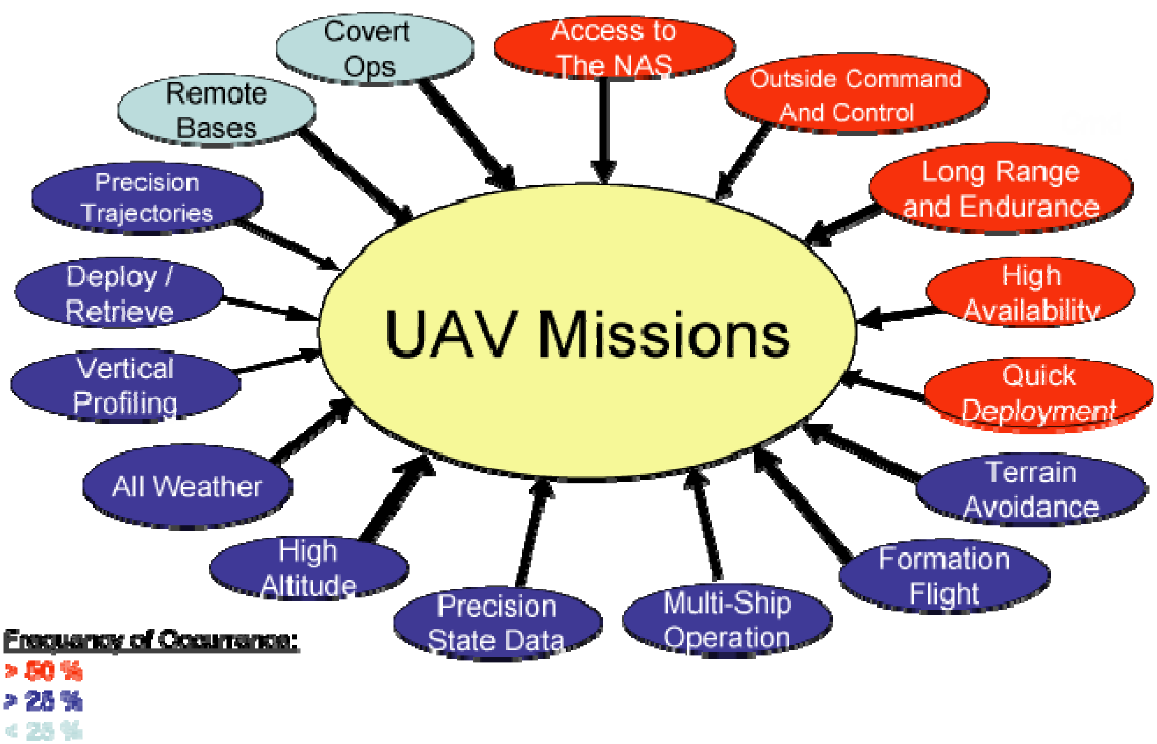

Figure D.1 - Key Capabilities Identified in Documented Missions

D.1 Access to the National Airspace System

Need: High

Virtually all of the missions discussed will require access to either the United States National Airspace System (NAS) and/or foreign air space at some point in the flight pattern. Even missions intended for remote areas require access to get the aircraft to the area. Often, this will require access not only to United States air space, but foreign air space as well. Access to the NAS can only be obtained through certification of the aircraft or through a waiver termed a Certificate of Authorization (COA). There currently exists no method to certify a UAV through the FAA. Therefore, all UAV flight within the NAS has been obtained through COAs thus far. A COA takes up to sixty days to obtain and permits only execution of a predefined mission flight path on specific dates at specific times and is typically valid for a very limited time period. Many of the missions require fast access to the air space. The use of a COA becomes unwieldy because of the application/receipt cycle of the COA being approximately sixty days. Many of the proposed missions intend to study phenomena which are not predictable sixty days in advance. The goal is to achieve seamless integration into the NAS (the so-called "file-and-fly" status) through certification which means that the flight may begin shortly after the flight plan is filed. This is the same system used for piloted aircraft. An FAA certification process must be established to achieve this. Several attributes of the UAV will likely be required to be granted certification. One of these is a method for the UAV to safely integrate into the air traffic system. This will require the UAV operator to respond in a timely fashion to commands from air traffic control. Typically changes to course, altitude, speed, etc. are required to avoid other air traffic. Another likely system is called contingency management which allows the vehicle to plan for an alternate course of action if something goes wrong requiring it to deviate from its original flight plan. Inherent in contingency management is a vehicle health management system which is capable of detecting anomalous conditions or situations. A third attribute is a collision avoidance system which allows the UAV to detect other aircraft and maneuver around them. In summary, the UAV must achieve the equivalent level of safety as a manned aircraft. A significant effort in systems sophistication, aircraft reliability, and policy/regulation development, including policy on operator training standards, will be required to accomplish this. The technologies discussed in Sections E.1 through E.5 are large contributors to this effort.

Current UAVs cannot fly in the air space in the manner described here. Developing the ability to provide "file-and-fly" was one of the goals of NASA's HALE ROA Access to the NAS project (often called Access 5). This project was to be accomplished in four steps.

1) Develop and recommend policy to the FAA for routine UAV flight above 40000 feet assuming launch and recovery in controlled air space.
2) Develop and recommend policy to the FAA for routine UAV flight above 18000 feet assuming launch and recovery in controlled air space.
3) Develop and recommend policy to the FAA for launch and recovery in designated ROA-capable airfields.
4) Develop the technology (if necessary) for sophisticated contingency management handling.

Currently, the program is unfunded. The Access 5 approach towards achieving these goals was a seamless integration of UAVs into the air space with little to no additional requirements being placed on existing piloted aircraft. Before UAVs can have file-and-fly capabilities, two other steps are necessary. Once the policy has been developed and recommended, it will still require FAA implementation. Finally, UAVs will likely need the on-board technology to satisfy the policies adopted by the FAA. The overall intent for routine operations in the NAS is Objective 6 of the GOTChA chart. Much of the technology required to provide this capability is discussed in other sections describing individual technologies, but integrating them into the airframe is not a trivial task. Access 5 only addresses United States air space. Clearance to fly in the air space of other countries is being addressed but is probably a little behind Access 5 pace. Currently, some areas (notably Africa and Australia) are UAV friendly. The ability to fly UAVs in other areas of the world is more limited.

D.2 Command and Control from an Outside Entity

Need: High

Typical UAV operations utilize a mission manager programmed during pre-flight to steer the vehicle around a prescribed course and altitude. Some mission managers will allow the operator to define new waypoints in flight. Future mission concepts require an ability for the aircraft's mission manager to be directed during its mission from a number of sources, including a ground-based operator or scientist observer, other aircraft (e.g. formation flying), a payload sensor, or satellites. This ability to re-direct a flight is instrumental for tracking dynamic phenomena such as hurricanes or volcanic plume, for adjusting to unplanned phenomena of interest, and for steering around unplanned obstacles, such as adverse weather, to meet a mission objective. An enabling technology to meet this capability is OTH communication, where a 'sensor web' approach to the mission can easily be achieved. One consideration is that allowing other entities to take control of the vehicle provides a mechanism that hostile entities (e.g. terrorists, hackers) can take advantage of. The system which develops must preclude takeover by any hostile operations.

Currently, some limited C^2 authority can be exerted from a ground-based operator on some UAVs. However, the technology required for future missions has much broader C^2 implications in terms of the level of autonomy it interfaces with and the infrastructure that is implied. One example is in the scenario where the payload sensor 'drives' the platform.

Formerly covered in the AuRA program, this technology is currently planned under NASA's HALE ROA demonstrator project, but it is only in its formulation stage. This capability supports Goal 5 of the GOTChA chart.

D.3 Long Range and Endurance

Need: High

Many of the missions conceive of a platform, or series of platforms, which clearly extend range and endurance beyond the capability of existing vehicles. These missions require ranges of 10,000 to 13,000 nautical miles (18500 to 24000 km) and endurances between 24 to 72 hours. A few of the missions indicated that endurances up to two to three weeks would be beneficial, if feasible. In particular the long-endurance requirements of these missions, as conceived, highlight the necessity for a UAV platform.

Some existing production UAVs are capable of endurance in the 24 to 36 hour time frame. A few, notably Northrop-Grumman's Global Hawk, have significant range capability. NASA, in conjunction with several private companies, is working on the technologies to enhance this capability. Under the HALE ROA demonstrator project, NASA is developing several new aircraft with long endurance (one to two weeks) capability. The largest advances in technologies for these aircraft will come in the propulsion and power generation areas. Improvements in both of these areas are Goals 3 and 4 of the GOTChA chart. Long range also supports Goals 1 and 2.

D.4 Increased Platform Availability

Need: High

A key development for enabling future missions will be to increase the availability of the science platform for collecting data. In other words, future missions will require that the ratio between the amount of time the platform is either on a mission or ready to start a mission to the total time the platform is on deployment be increased. One key component in increasing availability is the ability to significantly reduce the amount of time to pre-flight and launch a mission. This not only increases the availability of the platform for data collection, but also increases the likelihood of being able turn a mission around to collect data on dynamic events as they are discovered. Electrical and power interfaces will have to be standardized. The ability to integrate varied payloads in a 'plug and play' capability is necessary for quick deployments and for quick turn-around between missions where a sensor package may change. Intuitive flight planning tools and pre-flight processes and an efficient process for downloading and archiving on-board recorded data will also be key factors in reducing the time on the ground. And platforms must allow maintenance and pre-flight procedures to be performed easily and efficiently. Another key component to increasing availability is increased platform endurance, which allows the capability to extend mission duration. Analysis of current piloted Earth Science missions shows that significant costs are incurred based on payload integration and de-integration time and pre-flight and post-flight preparation time. An added benefit to increasing availability is a lower cost per flight hour, as the personnel required to be on station are reduced.

Current technology assessments indicate limitations on availability are based on human endurance, turn–around processes, payload, aircraft and payload maintenance processes, and data downloading and archiving procedures. Taking the on-board pilot 'out-of-the-loop' and smart integration of these processes with intelligent vehicle health management technology, autonomous mission management technology, and the OTH web-based approach to communication will allow much greater aircraft availability. For example, the ability of the flight planner to interface with the mission manager at the mission objective level will reduce the level of human involvement in pre-flight processes. Another example is the ability of the platform management system to identify when excess bandwidth exists in the OTH and then to download and archive on-board recorded data during the mission. This will reduce the level of human interaction in performing this function post-flight. NASA's Earth Sciences Capability Demonstration project is working on payload interface standards to facilitate the "plug-and-play" concept for payload integration. Much of this type of interface has not been done before and depends heavily on other technologies such as autonomous mission management. These capabilities support Goal 6 of the GOTChA chart.

D.5 Quick Deployment Times

Need: High

Several of the missions envisioned a UAV which could deploy within a few days to an area of interest and launch a mission to collect data on a dynamic phenomenon as it developed. The capability to quickly deploy ties together many of the other capabilities previously defined. Key enabling technologies are those that support access to the NAS, quick and efficient payload integration, an OTH network available when needed, and an intelligent mission management system which reduces pre-flight planning activity.

This capability is strongly linked with platform availability. Currently, quick and easy access to the NAS is not available but is being developed by NASA and the FAA. Payload interface standards have been developed to some degree and will be improved by NASA's Earth Science Capability Demonstration Project. OTH capability will also be improved by the same project. The intelligent mission management capability, formerly covered in AuRA, will be developed by NASA's HALE ROA demonstrator project. These efforts support Objective 8 of the GOTChA Chart. However, the integration of these technologies into a cohesive system has not begun.

D.6 Terrain Avoidance

Need: Medium

To increase the spatial resolution for some missions, a requirement is placed on the platform to fly 500 feet (152 m) above ground level or even lower. The missions envision the use of both mini aerial vehicles (MAVs) and UAVs in this capacity and may include flight in mountainous terrain. As such, complex flight path maneuvering and terrain avoidance is required of the platform's flight management system.

The technology for terrain avoidance and terrain following has existed for several years on military vehicles. Commercial airliners have employed an Enhanced Ground Proximity Warning System for many years. While the technology is available to implement this capability, the integration to the platform requirements still exists. This capability is included in Approach 10 of the GOTChA chart.

D.7 Formation Flight

Need: Medium

A technology related to precision trajectories is the ability to fly a formation of aircraft maintaining precise distances between them. Formation flight provides the ability to carry a synchronized set of scientific sensors on a team of coordinated vehicles. In a flight formation, one entity would be the "lead"; all other aircraft would fly relative to the lead. The lead could be another UAV, a piloted aircraft, or even a satellite. While it is not expected that an aircraft would keep pace with a satellite, the ability to position the aircraft relative to the satellite is desirable. Formation flight can be thought as two separate capabilities. The first is a series of aircraft which might be hundreds of meters to several miles apart. In this case, precision is desirable, but sensors would need to work over large distances. The second capability is close maneuvering wherein a pair of aircraft would fly relative to each other in close proximity. This capability would be used to accomplish air refueling as well as a small aircraft "docking" to a larger one. Proximity sensors for this requirement would probably be different from large-distance formation navigation and would require accuracies down to the several-centimeter level.

Most UAV operations involve one aircraft on a single mission. Objective 8 from the GOTChA chart calls for a significant reduction of human operators necessary to control a group of UAVs leading to a reduction in cost per flight hour. The closest system to the "distant" formation is DoD's station keeping equipment, but accuracies for this capability are far less than what is desired for precision formation flight. Some components of the close formation technology have been successfully flight tested in NASA's Autonomous Formation Flight program and in the J-UCAS program. These technologies can be leveraged to meet the future science mission capability for formation flight.

D.8 Monitor/Control of Multi-ship Operations

Need: Medium

Many of the future mission concepts require ground (operator) control of multi-ship operation and coordination. A key enabling technology which supports multi-ship missions is the OTH communication. Since a key motivation for using UAVs as an Earth science platform is reduced cost per flight hour, the ability of one operator to monitor multiple vehicles significantly reduces the support personnel required on-station. Also, some of the missions describe coordination with mini- or micro- aerial vehicles.

Currently UAV operations involve one aircraft on a single mission. The concept for future missions, where one operator controls a team of coordinated vehicles, is just beginning to be developed with MAVs and J-UCAS. Part of the J-UCAS program is to develop the capability of four or more UAVs to operate as a coordinated team. This effort supports Objective 8 of the GOTChA chart.

D.9 Precision aircraft state data

Need: Medium

Several missions required the ability to measure attitude data to relatively high precision (as high as 0.001 degrees). There is an additional requirement, however, for the aircraft to provide state data to the sensors or experiment packages. For example, the need for precise trajectories, accurate sensor pointing, and the onboard real-time geographic referencing of cameras all require accurate vehicle state data. The state data might be in the form of aircraft attitudes, position, ground speed, air speed, etc. While it is possible that each individual experiment package might measure their own data, this approach would be cumbersome, expensive, and inconsistent with the plug-and-play philosophy. Provisions should be made for the UAV to accurately measure its state data and make it available to the experiment package(s).

For the most part, current technology can provide instruments capable of generating state data to the desired level of precision. Therefore, this capability exists but must be specified in the requirements for a given platform, and there will be a cost associated with the requirement.

D.10 High Altitude

Need: Medium

Many of the missions require a platform, or series of platforms, capable of sustained flight at altitudes above 40,000 feet (12 km), with up to 100,000 feet (30 km) being desirable for some missions. A complicating factor in required aircraft design is performance for an aircraft which climbs to an altitude and cruises there versus an aircraft that must traverse wide altitude bands. The latter capability is called vertical profiling and is discussed later in this Appendix. An aircraft that will accomplish both high altitude and vertical profiling is decidedly more complex.

Although an important capability, the ER-2 and Global Hawk have routinely flown at most of the altitudes outlined in the future science missions. Therefore, the ability to fly at relatively high altitudes is an existing capability that only needs to be defined as a requirement in the aircraft development. One caveat is that some missions desired flight in the region of 100,000 ft (30 km) altitude. The Helios aircraft has flown in that altitude region, but it is considered to be a prototype and has limited payload capability. The inclusion of the 100,000 ft (30 km) requirement with a significant payload presents an added level of difficulty. High altitude technology supports Goals 1 and 2 of the GOTChA chart.

D.11 All-Weather

Need: Medium

Some of the missions, such as the Hurricane Tracking Mission, indicate that platforms are required to penetrate severe storms and fly in all types of weather, including icing conditions, strong wind shears, lightning, and severe convective environments.

Building a platform rugged enough to withstand flight in severe storms is within current technology. However this requirement places additional burdens on flight controls, and potentially platform performance goals, depending on the design solution of the system. For example, it would be difficult to develop a high altitude, long endurance aircraft (which may require a "gossamer" design) that would also survive high winds and turbulence. One design solution for performing these is to launch a series of rugged MAVs into the storm from a mother ship. The mother ship can meet performance requirements without the burden of meeting this all-weather requirement. The technology currently exists to build all-weather aircraft, but the requirement must be stated at the time the aircraft is developed. It is difficult to "retrofit" all-weather capability to an existing aircraft. All-weather capability will add to the cost of the aircraft design and construction.

D.12 Vertical Profiling

Need: Medium

Some of the missions depict the collection of spatial data in the vertical axis above a particular ground station of interest. Although drop-sondes can be used for a limited set of vertical spatial measurements, some of the missions envision the entire platform performing vertical profile maneuvers to collect the data. As such, the platform must deploy to a region of interest and collect data across a vertical profile from its altitude ceiling down to 1000 ft (305m) above ground level. This implies that the aircraft has sufficient performance and power to maintain a reasonable climb rate over the majority of its envelope which will impact the trade study for efficient climb versus efficient cruise.

Designing a flight management system to perform vertical profiling requires no new technology. Many current UAVs are capable of vertical profiling. However, the combination of vertical profiling and high altitude, long endurance may tax the aircraft designers.

D.13 Deploy / Potentially Retrieve

Need: Medium

One of the capabilities required for several of the missions is to have a UAV act as a mother ship for the deployment of drop-sondes, buoys, or small UAVs called daughter ships. In the case of the drop-sondes or buoys, the mother ship would release these at designated locations (pre-defined or initiated from the ground). The dispensing of drop-sondes or buoys is relatively simple but suffers from several drawbacks. First, the drop-sondes or buoys are not controllable; they are maneuvered only by the wind and gravity. Second, a long mission may require a large stock of drop-sondes or buoys to adequately cover the area of interest. This may have some significant consequences on mother ship payload weight and volume. Third, there are some environmental concerns about “littering” areas with many drop-sondes or buoys which may not be recoverable. An alternative to this approach is the use of daughter ships which would be launched, fly to an area to collect data, and then would fly back to the mother ship and re-dock. Daughter ship data would be downloaded to the mother ship and the daughter ship would be refueled for later use. This has the advantage that the daughter ships would be re-usable, so the mother ship would not need to carry nearly as many of them. The daughter ships would also be under the control of the mother ship so that precise areas for information gathering could be targeted. Daughter ships would be more complex and, consequently, more expensive, but their ability to be recovered and used again may offset the increased cost of purchase.

Deploying aircraft or drop-sondes from a mother ship has been done previously and does not require new technology developments. However, retrieving a daughter ship does require some technology development, principally in the area of precision state data and formation flying. Also, very little experience has been accumulated with the concept of re-docking. Lockheed-Martin has made some proposals involving launching and re-capture of UAVs. The common feeling is that if the technology exists to autonomously refuel a UAV, that same technology can be used to re-dock it. The concept of re-docking to a high altitude, long endurance aircraft is also without precedent.

D.14 Precision Trajectories

Need: Medium

Several missions require the location of the UAV to be controlled very precisely. Flight trajectories within ±5 meters from the prescribed flight path are desirable. This capability requires both the real-time knowledge of where the UAV is and the ability to control or maneuver the UAV to the desired position in the sky. Additionally, some missions have constraints on the dynamics of the flight path so that high-gain systems may not be suitable.

The development of UAV control systems to maneuver the aircraft correctly will be largely dependent on the characteristics of the UAV in question. For years, autopilots have been designed that follow a given trajectory. The issue is whether a particular UAV system can be adjusted to provide the desired precision. Unfortunately the ability to achieve the desired precision is dependent on the type of aircraft. Aircraft with light wing loadings and low speeds are more susceptible to crosswinds and gusts which may hamper the ability to maintain an accurate position. Regardless of the controllability characteristics of the UAV in question, this capability has been demonstrated. The Danish Center for Remote Sensing has demonstrated flights to approximately five-meter accuracy using a business jet. NASA's Earth Science Capability Demonstration Project is pursuing the capability to maintain aircraft position with a 10-meter (or better) tube. However, the integration to UAVs on a wide scale has yet to be demonstrated.

D.15 Base of Operations in Remote Area

Need: Low

The capability to deploy a small, inexpensive UAV from a remote location near an area of interest was conceived to obtain specific scientific data in remote areas. The requirement for this capability is a UAV platform which requires very little support equipment and minimal personnel for pre-flight, launch, and recovery. With this capability, range and endurance requirements on the UAV platform can be reduced. This concept may also impact the mode of operation for an autonomous ground station which could pave the way for a planetary-exploring UAV.

Certainly MAVs can be launched with minimal support personnel and equipment without any advances in technology; however the concept of a fully automated ground station has not been demonstrated. Using them for the Earth Science application may depend on payload sensor technology advances, since payload weight and volume capability is limited. Also, it is likely that high levels of automated mission management, intelligent flight control, and health monitoring may not be available because of the limited computation resources on a MAV. Therefore payload sensors on a MAV may have to be expendable. The construction of a more sophisticated, even autonomous, base of operations in a remote area (even the Moon or another planet) remains in the conceptual state only.

D.16 Covert Operations

Need: Low

A subset of the missions, primarily from the Homeland Security and wildlife monitoring communities, required platforms with low detection probability. Implied in this requirement is low noise emission propulsion systems and low signal emissions.

Conventional propulsions have undergone low noise emission developments to support stealth for the military application and airport considerations for the commercial sector. Although certain propulsion systems, such as electric motors, provide very low emissions, it is unclear they can sustain some of the endurance and payload requirements envisioned in the missions. Development programs to enable more efficient electric motors are being conducted in both the commercial and government sectors that may enhance the capability for low noise operations.

Appendix E

UAV Technologies

Technologies

The following sections describe each technology in detail, summarizing development programs and forecasting maturation over the next 10 years. A determination of when the technology will have matured enough to support the capabilities identified from the missions is provided where appropriate. More detailed information on the technology development can be found in Appendix I, the inputs from the Technology Working Groups (TWG). Within the title of each technology section, a first-cut estimate of the need of that technology or capability is given. If the technology supported at least half of the missions, it received a "High" rating. If it supported at least 25% of the missions, it earned a "Medium" rating. The remainder (those supporting less than 25%) were rated "Low". It should be noted that the ratings do not imply priorities.

Where available, the Assessment team provided preliminary estimates of Technology Readiness Levels (TRLs) for each of the technologies. These estimates are subjective in nature and subject to change from on-going research or from subject matter expert opinion.

Future editions will include the following information:
- Identification and description of sub-set technology components.
- Summarization of technology and technology sub-set components maturation over time.
- Identification and summarization of key development programs.
- Summarization of technology development ability to support desired capabilities.

E.1 Autonomous Mission Management

Need: High

A high level of autonomy in the mission management function is required to take advantage of using a UAV platform to support the missions. Less direct human interaction in flying the UAV allows less on-station personnel, less on–station support infrastructure, and one operator to monitor several vehicles at a given time. These goals must be balanced with the requirement for the operator and vehicle to respond to air traffic control in a timely manner. The mission management system should also allow re-direction of the mission (including activating the contingency management system) from the ground. This would especially be useful for moving phenomena which cannot be adequately located prior to mission initiation. It is envisioned that the human interaction with the on-board mission manager system will occur at the mission objectives level. In the ideal scenario, the on-board mission manager, starting with the mission objectives, would be responsible for pre-flight planning, real-time flight path adjustments during the mission, and even real-time mission objective adjustments during the mission based on air traffic control and contingency management. It is also desired for the scientist or possibly the payload sensor to interact with the mission manager, as well as the operator responsible for the mission. Providing these functions will require a shift in the paradigm of how flight management software is currently written. The desired system is an open behavior system. This approach enables much of the capability conceived in the future missions, such as efficient mission re-tasking, increased platform availability, efficient contingency management, and coordinated team formation flying. As such, it is highly dependent on the current condition at the time a behavior is executed and is difficult to precisely predict. Increasing the complexity is the fact that any intent to deviate from the original mission plan must be first conveyed to and approved by air traffic control prior to being executed. The level of autonomy in the system presents significant human factors challenges to the operator, who must maintain sufficient situational awareness of the intention and execution of the platform to fulfill his responsibility.

The level of autonomy in the future mission management function is significantly more sophisticated than exists with current UAVs. Additionally, verification and validation of these systems will be a challenge. Currently the Joint Unmanned Combat Air System program (J-UCAS) is employing a similar software approach to mission management. NASA, under the HALE ROA demonstrator program, is also working on a similar Intelligent Mission Management system. Autonomous mission management supports Approach 9 of the GOTChA chart.

The TRL is estimated at 4, since some components of these methods are modeled in the simulation environment.

E.2 Collision Avoidance

Need: High

To fly with few restrictions in the NAS, UAVs will require some sort of collision avoidance system. The intent is to have an “equivalent level of safety” when compared with piloted aircraft. This system will allow UAVs to “see” or detect other aircraft (piloted or uninhabited) and avoid them. The technology for this system is decomposed into two elements “see” and “avoid”. The “see” portion involves the detection of intruding aircraft through some type of sensor. The “avoid” portion involves predicting if the intruding aircraft poses a danger and what course of action should be taken through a software algorithm. For sensors, the priority should be to detect aircraft at sufficient distance so that emergency maneuvering can be avoided. The first step in this development will be to implement a <u>cooperative</u> sensor for collision avoidance. Under the cooperative category, aircraft will have transponders or data links notifying other aircraft of their position. The second and more difficult portion is <u>non-cooperative</u> detection. In this case, the “other” aircraft does not share its position (as would be the case for many general aviation aircraft) and must be detected with radar or optics. For avoidance, sensor information must be used to predict future positions of host and intruder aircraft to determine collision potential. If a collision potential exists, a safe escape trajectory must be derived and automatically executed if the operator has insufficient time to react.

Some significant work has already been done in this area. The NASA ERAST-project tested both a cooperative and non-cooperative sensor. Also, the Air Force has completed a project evaluating an avoidance algorithm coupled to an automatic evasion maneuver. Both cooperative and non-cooperative sensors were demonstrated in the Air Force project with promising results. Collision avoidance systems are also being worked on under NASA HALE ROA Access to the NAS project, and collision avoidance supports Objective 7 of the GOTChA chart.

The overall TRL for collision avoidance technology is estimated to be at 6. However, since no viable non-cooperative sensor or sensor suite has been developed to date, the UAV requirement for this technology is rated at a TRL of 2.

E.3 Intelligent System Health Monitoring

Need: High
The ability of a UAV system to reliably identify failures and classify them according to their impact on vehicle safety and mission success is a key technology for flying UAVs with an acceptable level of safety. This technology, generic to any UAV application, allows intelligent contingency management based on the failed vehicle state and is a foundation for free access to the air space by UAVs. Additional cost benefits are accrued by using this system to monitor sub-systems for maintenance purposes. Identification of sub-systems as they deteriorate will focus maintenance efforts, decreasing the turn-around times between missions and reducing costs per flight hour.

Health monitoring concepts and limited systems have been around for some time, but comprehensive and generic systems have languished due to lack of funding. Specific systems have been developed and proven, particularly for new fighter aircraft. Additional work is in progress under NASA's HALE ROA demonstrator project (previously under the AuRA program). Intelligent system health monitoring is covered under Technical Challenge 6 of the GOTChA chart.

An overall TRL of 5 is estimated.

E.4 Reliable Flight Systems

Need: High
The ability of a UAV flight system to adapt to system or hardware failures is a key technology for flying UAVs with an acceptable level of safety and perhaps the most critical system for the aircraft is the flight control system. This technology, generic to any UAV application, provides for high reliability and is one of the foundations for unrestricted access to the air space by UAVs. Initial reports from the FAA regarding UAVs indicate they are looking for "reliability comparable to a piloted aircraft". The issue of reliability can be addressed from two viewpoints. The first is basic reliability of the onboard systems. The second is the reliability of an on-board pilot in being able to recognize a failure and adapt to the situation (see the next Section on Sophisticated Contingency Management). Both of these viewpoints must be considered in assessing the reliability of UAV flight systems. This technology is especially important for long endurance flights in remote areas, where options for recovery are limited.

One approach to system reliability is simply to increase the redundancy of flight systems. This comes with both an initial cost and an on-going weight penalty. Another approach would add on-board intelligence to recognize and remedy a failure. Simulations of adaptive flight control systems have shown promise for many years, and several methods of adaptive control have found their way to flight test projects. The latest of these is a neural-net based system scheduled to fly on an F-15 aircraft at NASA. It is likely that the final solution will be a compromise or combination of the two approaches. Efforts on reliable flight systems for UAVs are supported by Approach 9 of the GOTChA chart.

Based on ongoing intelligent flight control efforts, a TRL of 6 is assigned.

E.5 Sophisticated Contingency Management

Need: High

UAV operation will require some level of contingency management system for all flights in the NAS. The on-board contingency management system should be able to react to unforeseen events and failures such as the following priorities:

- Minimize expectation of casualty (Ec)
- Minimize external property damage
- Maximize the chance of aircraft survival
- Maximize the chance of payload survival

For the long term, it will be unreasonable to consider many UAVs as expendable. In addition to the cost of UAVs, the cost of its sensor suite (which may be one-of-a-kind) must be considered. Loss of the UAV and payload should only be considered when there is a significant risk to the general public or property. One of the primary contingencies to be planned for is the loss of link between the UAV and the operator. In this case, if the vehicle cannot continue on its original mission plan, the vehicle should have the capability to achieve an approved landing area while considering the priorities above and attempting to re-establish the communications. During these events, the UAV must have alternate means to communicate its intended flight plan. However, other contingencies must also be considered. These might include sensor or payload failures, aircraft failures, and other communication failures. The contingency management system should be able to decide, depending on the nature of the problem, whether it should attempt landing at the airport it was based out of, or landing at an alternate airport, or some other impact (ditch) in a remote area. Intelligent contingency management will also reduce the human oversight required for UAV flight and contribute to the goal or reducing mission costs.

Contingency management for UAVs at the level described will require a sophistication that currently doesn't exist. Relatively little development of this capability has occurred to date although several promising concepts have been proposed. Global Hawk and Predator have contingency management systems to some degree, although they lack the sophistication and intelligence that would be desirable for ease of use. NASA, under the HALE ROA Access to the NAS project, is currently working to define a UAV "code of ethics" and policy regarding contingency management systems. Contingency management supports Objective 7 of the GOTChA chart.

An overall TRL of 4 is assigned.

E.6 Intelligent Data Handling and Processing

Need: High
As UAVs become more ubiquitous in their use to gather science data or perform other civilian tasks, the gathering of very large amounts of data will become an operational hindrance, and provide an opportunity to the system developer. The ability to intelligently handle and process large amounts of data, either onboard the air vehicle, or on the ground immediately after being transmitted from the vehicle, is required. Technology that would provide this capability would significantly provide greater efficiency to the operator or payload scientist, and would help expedite vehicle turn-around, quick deployment, and multi-ship operations; particularly for long-endurance missions. If this data analysis capability were to be available on the ground, and if high-bandwidth communication (probably satellite based, to enhance the timeliness of the action) is available, the air vehicle could transmit the data to the mission control center for quick analysis and possible mid-mission re-tasking.

The ability to process the data on-board goes a step further and becomes even more useful, because it doesn't require a high-bandwidth satellite communication (SATCOM) capability. Intelligent onboard data handling and processing would lead to the use of onboard decision aids and intelligent payload-based mission management technology, which could result in efficient onboard mission re-tasking. Alternatively, onboard processing could allow only low-bandwidth high-order processed data to be relayed to the mission planners for decision-making and mission re-tasking if necessary.

In addition, onboard processing and transmission could allow scientists quick and easy data retrieval, which could relate to faster post-mission processing and the beginning turn-around processing, all while the vehicle is still returning to base.
Intelligent data handling and processing would require technology innovations in automation and autonomous data analysis systems, efficient and effective techniques for assembling and processing large amounts of data, and intelligent searches of large distributed data sets.

For this technology, a TRL of 2 is estimated.

E.7 Over-the-Horizon Communication

Need: High
A key technology that supports almost all of the future missions is the ability to transmit data OTH. This satellite-based communication capability is being used by the military today to provide UAV OTH C^2, FAA air traffic control communication, and sensor data transmission. Although low-bandwidth OTH communication is used by civilian UAVs, access to OTH resources for high-bandwidth civilian use is limited and needs to be expanded. Also, the issue of OTH communication being non-interruptible jam resistant,

damage tolerant, and all-weather capable, must be addressed. The OTH technology must also include the ability to pass high bandwidth data from remote areas or at extreme latitudes such as the poles.

In addition, it will be very valuable to develop a “web-based” network capability to OTH communication (see Network-Centric Communication technology section). The vehicle, operator, and payload scientist would be seen as nodes of the network. For example, this approach means that an operator in California could control an aircraft flying over the North Pole while a scientist in Washington, DC was monitoring the vehicle’s science data. Additionally, this network concept for OTH communication should be configurable based on the data flow requirements for a given mission. In other words, the network should be able to provide the level of bandwidth required for a given mission so that missions which don’t require high bandwidth communication do not have to pay for the resources necessary to effect it. This technology will reduce the cost per flight hour by creating more efficient data handling and reducing the need for personnel at the base of operations.

However, the concept described here significantly expands the concept of OTH communications. Adjustable bandwidths and a ‘web-based’ use are concepts that still require significant technology developments. There is strong interest in this concept from both civilian (NASA) and DoD agencies. NASA is pursuing this technology under their Earth Sciences Capability Demonstration project in conjunction with the Integrated Network Enhanced Telemetry (iNet) efforts.

For this technology, a TRL of 3 is estimated.

E.8 Network-Centric Communication

Need: High

Network-centric communication is a C^2 and sensor data communication architecture concept that is comprised of multiple directional, asymmetric links that provide a network communication approach – similar to the Internet. This communication architecture is under development by the military for use between manned and unmanned air vehicles and personnel within a particular battlespace – but it is also needed to enhance civilian UAV operations, communications, and science data flow. For a given mission, key elements within the UAV’s mission are to be considered as a node; data can then flow to and from any node to any other node. Examples of nodes are the UAV operator, a scientist observer, the vehicle platform’s mission manager, satellites orbiting overhead, the vehicle’s payload, other aircraft, remote C^2 locations, etc.

Although the obvious key benefit is increased C^2 and data routing flexibility, this same flexibility also adds communication signal protection, allowing entirely different received and transmitted radio waveforms that can be used to advantage to provide more secure communication.

In concept, the network should be available with very little interface required by the mission planning team. Additionally, the network should be bandwidth configurable based on the data flow requirements for a given mission. This technology will reduce overall operational cost by creating more efficient data handling and reducing the need for personnel at the located at the UAV's primary base of operations.

NASA is pursuing this technology under their Earth Sciences Capability Demonstration project in conjunction with the Integrated Network Enhanced Telemetry (iNet) efforts.

For this technology, a TRL of 3 is estimated.

E.9 Open Architecture

Need: High
Many civilian UAV mission requirements include quick deployments and/or quick turn-around times between flights. These requirements have implications on the UAV's system architecture – and thus the need for open architecture.

Open architecture is envisioned as a system design technology that literally provides a "plug and play" capability within the UAV system. If a UAV system or its modular payload component has an operational problem – ground maintenance personnel can easily and quickly replace the faulty element. Sensors, sensor systems, and even mission payloads could be designed as modular components for easy change-out between storage and air vehicle, or from air vehicle to air vehicle – in some cases, even if the air vehicles are different.

Open architecture could encompass the advanced communications systems network at well. As the air vehicle's communication system moves toward a more generic network-centric design, some vehicle-system communication elements could be designed with the same quick change-out methodology as well.

For this technology, a TRL of 4 is estimated.

E.10 Power and Propulsion

Need: High
Many missions call for flight to high altitudes, long endurance, or flight within "dirty" air (such as through the smoke plume of a forest wildfire). Such missions will require specially designed power and propulsion technologies.

A high-altitude flight requirement typically dictates the use of turbine engine propulsion – or for slower flight, the use of electric propulsion; each of which are well developed and demonstrated at this point. If internal-combustion engine technology is desired for this flight requirement, due to its inherent low cost and relatively low rate of fuel consumption, a two-stage turbocharger can be used – and this has been demonstrated.

For long endurance flight, the propulsion options are varied, and continue to be developed. Typically, conventionally powered long-endurance vehicles require a fuel load equal to 40% to 60% of their gross takeoff weight. This, in turn, provides design and payload tradeoffs that can limit function. Another method that has been used with long-endurance UAVs is to use solar power and electric propulsion. Solar power cells, more technically known as “photovoltaic (PV)” cells, are not very efficient (with modern technology conversion factors on the order of 18%-21%), and the amount of energy provided by the Sun over a unit area is relatively modest. This means that a solar powered aircraft must be lightly built to allow low-powered electric motors to get it off the ground. Considerable technology development in this area is required.

Clearly, for long endurance and high altitude flight, electric propulsion is a key technology and one that holds great promise. New technology is being developed in many areas: high-efficiency and high-torque brushless “outrunner” motors, advances in non-silicon flexible PV technology that could be used as embedded aircraft skin, advanced standard and regenerative fuel cells, and advances in lithium polymer battery technology hold great promise. Other relevant technologies could also enhance long endurance flight with conventional engines: efficient combustion technology, intermittent combustion, hydrogen engines, and new efficient power management and distribution technology are being pursued.

For the advanced technologies discussed, TRLs are estimated to vary within the range of 3 to 5.

E.11 Navigation Accurate System Technology

Need: Medium

Navigational accuracy within the UAV’s on-board system is required for a number of mission tasks. For example, the need for precise trajectories, accurate sensor pointing, and the onboard real-time geographic referencing of EO or IR pictures, all require accurate vehicle position and attitude data.

Such navigation accurate technology can be obtained with current technology. A vehicle’s position can be easily obtained on-board with a GPS receiver. And the vehicle’s 3-axis attitude can be determined with an onboard inertial measurement unit (IMU).

However, standard GPS data may not be sufficiently accurate. In this case, the use of differential GPS (dGPS) data, to correct the embedded random GPS errors, may be necessary. This is readily available real-time to a UAV by use of a small omni-directional antenna and a subscription to commercial satellite-based data. Normal computation drift of a miniature IMU can also be self-corrected by use of the accurate GPS data. NASA’s Jet Propulsion Laboratory has flight tested a Global Differential Global Positioning System (Global dGPS) which advertises accuracies in the 10 centimeter range over populated land areas and 50 centimeter range over areas like the North and South Poles.

This navigation and attitude data is then used to either point an on-board camera to a desired GPS location on the ground; or the reverse, to calculate the ground location of an object that was visually captured by the science payload.

All of this is currently being used on large UAVs, but the technology development required is to miniaturize this technology for use on small UAVs and thus expand the mission utility to these vehicles.

For application to a small UAV, the technology is estimated at a TRL of 4.

E.12 Enhanced Structures

Need: Medium

The flight performance and utility of a UAV designed to fly either at high altitude or with long endurance, or both, can sometimes be significantly constrained due to the weight and design limitations placed on these unique aircraft by the aircraft's structure. Conventional structural materials provide adverse penalties on vehicle weight and design flexibility.

The use of advanced low-weight structures, and advanced low-cost composite manufacturing methods, and active flight elements, will allow significantly reduced structural weight and the use of bold, unconventional aerodynamic designs. This, in turn, can significantly enhance the useable science payload size and weight.

New lightweight material development, flexible structural controls, "morphing" aircraft airfoil and platform shapes, and active flight controls for gust alleviation and to maximize performance efficiencies may have significant impact in this area.

For the advanced technologies discussed, TRLs are estimated to vary within the range of 1 to 3.

Appendix F

UAV Sector GOTChA Chart

Overview

As referenced in several places within the main body of the document, Figure F.1 is the GOTChA Chart. Many of the general and specific capabilities have been captured in NASA's UAV Sector "GOTChA" chart. The GOTChA used in this assessment is for illustrative purposes. It was developed by the UAV Sector of NASA's Aeronautics Research Mission Directorate. Because of organizational restructuring at NASA Headquarters, this organization does not exist. However, for purposes of defining a potential program, this example provides a wealth of information.

The GOTChA chart is a management tool that breaks down the Goals, Objectives, Technical Challenges, and Approaches of a project – in this example, improving the state-of-the-art for UAV missions to perform Earth science observations.

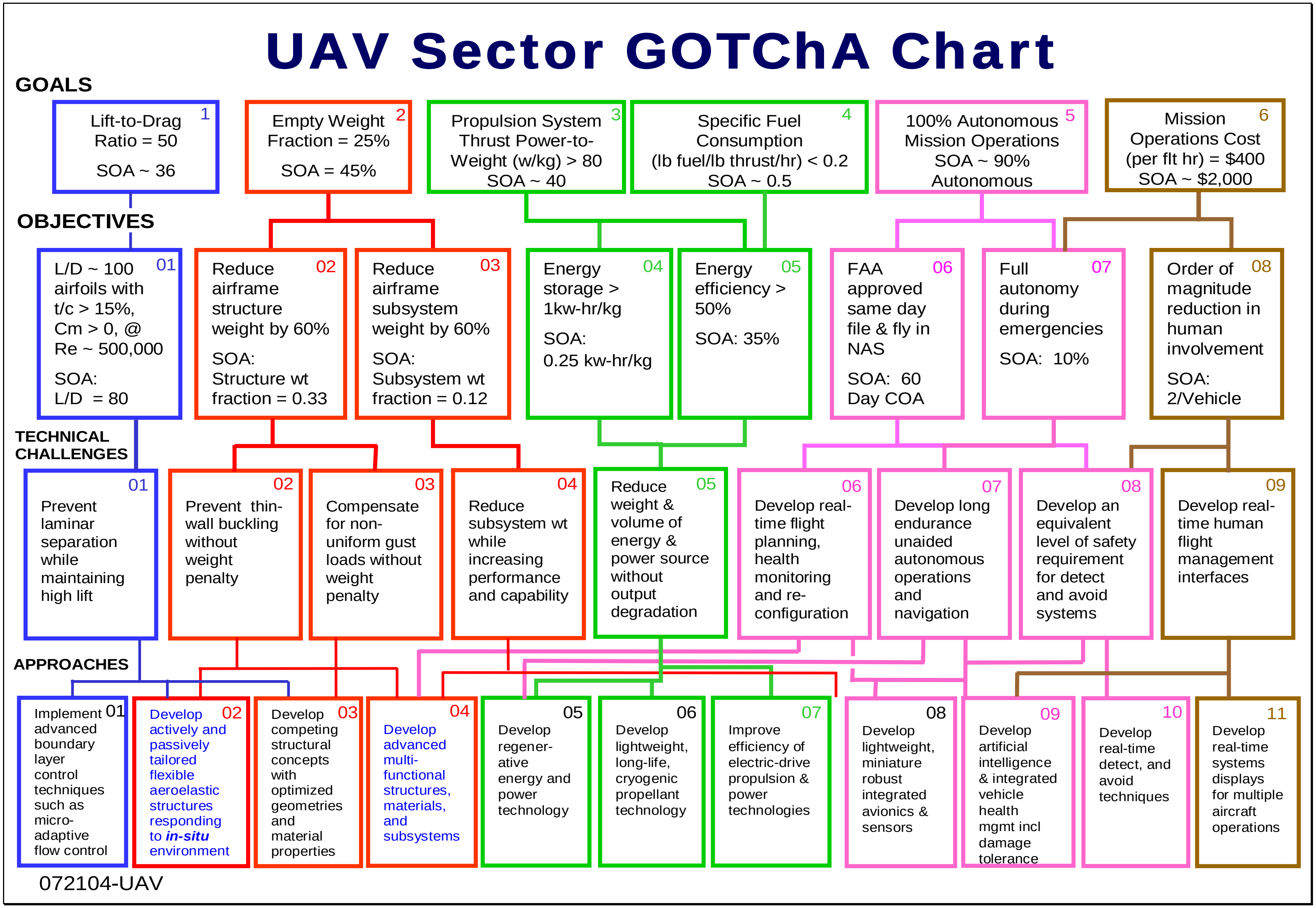

Figure F.1 UAV Sector GOTCHA Chart

Appendix G

Technology Readiness Levels

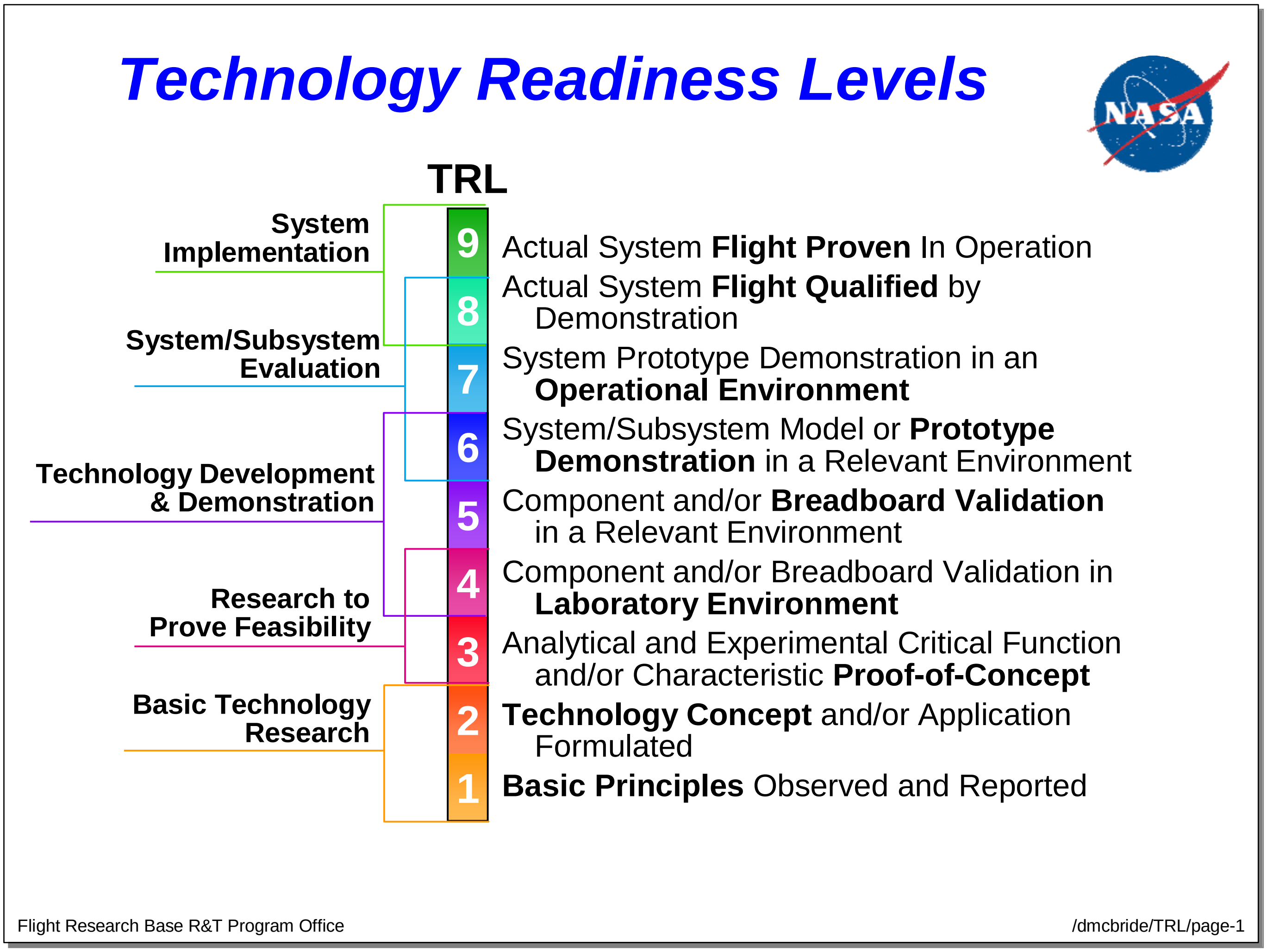

Figure G.1 - Technology Readiness Levels

Appendix H

Technology Working Groups' Inputs

H.1 Overview

This appendix discusses technology maturation and development data, which will be used to support the time-based estimates of a particular technology's availability for inclusion into a UAV system. Technology maturation forecasting is based on programs and development schedules. The basis for this information was formed from technology working groups, consisting of technology subject matter experts across NASA, other government agencies, private industry, and universities. Included in this appendix are technology forecasting models and methods utilized by the assessment team and the working groups, as well as templates provided to the working groups to collect the relevant data. The completed templates as well as the USRA peer review report are contained in Volume 3.

H.2 Technology Forecasting Models and Methods

H.2.1 Introduction

Forecasting is hard, particularly of the future. [Anonymous]

Forecasting is like trying to drive a car blindfolded and following directions given by a person who is looking out the back window. [Anonymous]

Technological Forecasting (TF) is defined as the process of predicting the future characteristics and timing of technology. When possible, the prediction will be quantified, made through a specific logic, and will estimate the timing and degree of change in technological parameters, attributes, and capabilities. (*Technological Forecasting*, Meredith, JR and Mantel, SJ, University of Cincinnati, 1995.) Note that in the definition, TF is aimed at predicting future technological capabilities, attributes, and parameters. It is not an attempt to predict how things will be done; nor is technological forecasting oriented toward organizational profitability. The focus of TF is to estimate when a technological capability or attribute can be forecasted to be available at some time in the future. TF is not focused on societal aspects since society may not necessarily want or need the capability.

H.2.2 Assumptions to TF

There are several assumptions about forecasting that must be understood by the using and performing organizations, including:

- There are no methods to predict the future state of a technology with complete certainty. Regardless of the methods employed, there will always be some degree of uncertainty until such time as the forecasted horizon has come to pass.

- There will always be “holes” or blind spots in any forecast. For example, it is not possible to forecast accurately completely new technologies for which there are no existing paradigms on which forecasts can be built.
- Providing forecasts to decision-makers will help them formulate organizational policy. The new policy, in turn, may affect the future and impact the accuracy of the forecast.
- Forecasting is an iterative process that requires periodic updates and substantiation.

H.2.3 Types of TF Models

Two types of TF models are the Numeric Data-Based Technological Forecasting Techniques and Judgment-Based Technological Forecasting Techniques. A brief description of some of these models follows (a more robust description can be found in the references in Appendix I):

H.2.3.1 Numeric Data-Based Technological Forecasting Techniques

Trend Extrapolation infers the future from events occurring in the past. If there has been a steady stream of technological changes and improvements, there can be a reasonable assumption that these changes and improvements will continue into the future. The literature identifies five approaches to the use of trend extrapolation.

- **Statistical Curve Fitting**

This method is used to forecasting functional capabilities. Statistical procedures fit the past data to one or more mathematical functions such as linear, logarithmic, Fourier, or exponential. The best fit is then selected by statistical test and then a forecast is extrapolated from this mathematical relationship.

- **Limit Analysis**

In the extreme, all growth is limited, and there is an absolute limit to progress, either recognized or unrecognized. Sooner or later, projections must reflect the fact that improvements may get close to this limit but cannot exceed it. For instance, a trend of increasing energy conversion efficiency cannot eventually exceed 100 percent. If the present level of technology being forecast is far from its theoretical extreme, extrapolation may not be unreasonable. If, however, a current technology is approaching its limit, and if this is not recognized, projections of past improvements may seriously overestimate future accomplishments.

- **Trend Correlation**

Often, one technology can be described as a precursor to another. This occurs when advances made in the precursor technology can be adopted by the follower technology. When such relationships exist, knowledge of changes in the precursor technology can be used to predict the course of the follower technology, as far in the future as the lag time between the two. Further, extrapolation of the precursor allows a forecast of the follower to be extended beyond the lag time. An example of a trend correlation forecast is predicting the size and power of future computers, based on advances in microelectronic technology (similar to Moore’s Law).

- **Multivariate Trend Correlation**

Occasionally, a follower technology is dependent on several precursor technologies rather than on a single precursor. In such cases, the follower is usually a composite or aggregate of several precursors. Fixed combinations of the precursors may act to produce change in the follower, but more often the combinations are not fixed and the precursor inputs vary in both combination and strength. For example, improvements in aircraft speed may come from improvements in engines, materials, controls, fuels, aerodynamics, and from various combinations of such factors.

- **Trend Extrapolation, Qualitative Approaches**

Often, standard statistical procedures may not result in neatly fitting trends that the forecaster can extrapolate with any degree of confidence. In such cases, the forecaster may "tweak" the statistical results by applying judgment or may ignore the statistical inferences entirely and extrapolate a trend based on personal judgment. Forecasts generated in this way are less precise than statistically based forecasts, but not necessarily less accurate.

Models of this approach include:

- Growth Curves
- Envelope Curves
- Substitution Model

H.2.3.2 Judgment-Based Technological Forecasting Techniques

- **Monitoring**

Many forecasting techniques presuppose that the user is fully aware of what the end goal is. Although the technologists may have considerable expertise, there may be some unexpected technological surprises in store. Monitoring, or innovation tracking, allows forecasters to stay cognizant of technologies as they develop. The basis of this approach assumes that a new discovery goes through several stages before emerging into public view as an innovation, and that some future technologies are in the process of development, The stages to investigate are:

- Initial idea or suggestion-the concept
- Postulation of theory-the research proposal
- Verification of theory-the scientific finding
- Laboratory demonstration
- Field trial
- Commercial introduction
- Widespread adoption

Monitoring is basically the technology development cycle contained in any in-depth discussion of technology life cycle.

- **Delphi Method**

The best known of the various judgmental approaches to technological forecasting is the Delphi method. This approach uses a panel of individuals who make anonymous, subjective judgments about the probable time when a specific technological capability will be available. The results of these estimates are aggregated by a process administrator and fed back to the group, which then uses the feedback to generate another round of judgments. After several iterations, the process is stopped and areas of agreement or disagreement are noted and documented. Software packages that perform the administrative actions are available and make the process less cumbersome. The Delphi process includes the following steps:

- Opinion Gathering and Distribution
- Iterative Balloting
- Reasons and Consensus
- Group Composition

Other judgment-based technological forecasting techniques include:

- Network Analysis
- Scenarios
- Morphological Analysis
- Cross-Impact Analysis
- Relevance Trees

Detailed discussions on all of these techniques are found in the references contained in Appendix I.

H.3 Technology Templates

Two technology templates were provided to the Technology Working Groups (TWGs) to structure the collection of data and to help ensure consistent methods across the relevant technology areas. As deemed appropriate, each technology was split into sub-components based on the view of the TWG members. An additional template was developed to collect and document the technology status for each sub-component of relevant technologies. For example, power and propulsion technology is considered one of the enabling technologies for UAV missions. Within power and propulsion, there exist “sub technologies,” including advanced fuel cells, internal combustion engines, power distribution systems, etc. Detailed information on each of these sub-component technologies become inputs from the TWGs. It is expected that these sub-levels can be utilized to assess the overall maturation of the technology of interest. Figures H-1 and H-2 represent the broad technology and the sub-level templates, respectively.

The templates were provided to each working group leader to collect and document and summarize that technology area based, in part, on the information in the sub-component technology template, as needed.

Enabling Technology: ____

Contributing Editor: ***Date:***

Phone: **Fax:** **Email:**

Enabling Technology Description: *Describe briefly the general nature of the technology. How does it support the capability required? This should describe the uniqueness of the technology and project a clear idea of its contribution to UAV capabilities. Are there limitations of the applicability of this technology?*

Current State of the Technology: *Provide a short summary including current TRL and basis for this assessment.*

Identify funded programs that contribute to the development of this enabling technology. Will these programs support TRLs needed for maturation?

Are there specific technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:

Forecast of enabling technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast. What is the time estimate for this enabling technology to be ready to support the capability for the mission?*

Identify and articulate any technology gaps discovered:

Enabling Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					
Demonstrated for UAV application?:					

Figure H.1 – Enabling Technology Template, Broad View – page 1 of 2

Technology Assessment – Resource & Research Summary

Known sources of information:

Capabilities (must have, etc.):

Research being done:

Regulatory/security issues? ITAR:

Non-US efforts:

List Any Assumptions:

Figure H.1 (continued) – Enabling Technology Template, Broad View – page 2 of 2

Enabling Technology:__________________

Specific Technology:
Contributing Editor: ***Date:***
Phone: **Fax:** **Email:**

Specific Technology Description: *Describe briefly the general nature of the technology. How does it support the capabilities required? This should describe the uniqueness of the technology and project a clear idea of its contribution to UAV capabilities.*

Current State of the Technology: *Provide a short summary including current TRL and basis for this assessment.*

Identify funded programs that contribute to the development of this specific technology

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Are there critical supporting technologies/dependencies that need further development for this technology to reach maturity? Identify technology and source and explain:

Identify funded programs that contribute to the development of the critical supporting technology:

Forecast of specific technology: *Provide a forecast of the TRL progress as a function of time. Please provide any assumptions and rationale for this forecast.*

Specific Technology Cost Drivers: *Operating and development costs.*

Known competing or disruptive technologies:

Major Events/Milestones:

	2006	2007	2008	2009	2010
Event:					

Demonstrated for UAV application?: (text)

Figure H.2 - Specific Technology Template, Sub-Level View – page 1 of 2

Technology Assessment – Resource & Research Summary

Known sources of information:

Research being done:

Regulatory/security issues? ITAR:

Non-US efforts:

List Any Assumptions:

Figure H.2 (continued) - Specific Technology Template, Sub-Level View – page 2 of 2

Appendix I

References and Information Sources

I.1 Overview

This appendix contains references and background materials utilized in developing the list of potential missions. The structured approach used the questionnaire shown in Section I.2 and a guideline in gathering responses from subject matter experts and those interested in proposing potential missions.

Section I.3 lists many of the sources for the document and Section I.4 is a list of reference materials for detailed technology forecasting background.

I.2 Interview Form and Organizations/Agencies Represented

I.2.1 Organizations/Agencies/Private Sector

The organizations represented at the various workshops and conferences along with those that participated in the interview process are articulated in this section. It should be pointed out that only the top organizational name is given. For example, although NOAA is listed once, the Team recognizes that participants from the many applicable divisions and laboratories were contacted for inputs. The Assessment Team has the rosters of all attendees at the workshops and of those that participated in the interview process.

- **Government Agencies**

Department of Defense
Department of Energy
Department of Homeland Security
Department of the Interior
Federal Aviation Administration
NASA AMES
NASA DFRC
NASA GRC
NASA GSFC
NASA HQ
NASA JPL
NASA LaRC
NASA MSFC
National Oceanic and Atmospheric Admin.
National Science Foundation
US Geological Survey
USDA National Forest Service

- **Academic Institutions**

California State Univ., Monterey Bay
California State University, San Diego
Colorado State University
Columbia University
Florida State University
Georgia Institute of Technology
Hampton University
Harvard University
Ohio State University
Penn State University
Purdue University
Universities Space Research Association
University of California, Davis
University of California, San Diego
University of Colorado
University of Denver
University of Illinois
University of Kansas

University of Maryland
University of Michigan
University of Southern California
University of Utah
Woods Hole Oceanographic Institution

- **Private Sector Organizations**

EGG Technical Services
GTP Associates LLC
Longitude 122 West, Inc.
Lynne Carbon & Associates, Inc.

I.2.2 Interview Form

Civil UAV Capability Assessment – Customer Interview Form

Rev. Date: 1-Jul-04

Customer ______________________ Phone ______________________

Agency or Company ______________ Division ____________________

Date of Interview _________________ Interviewer ___________________

(What is your current "State of the Art"?)
What is your current mission requirement?

- Payload
  - Image based Surveillance
  - Environmental Sampling
  - Payload Delivery
  - Communications
  - Serviceability
  - Other ________________________
- Flight Environment
  - Proximity to Population
  - Altitude
  - Range
  - Endurance
  - Climate
- Monitoring Requirements
  - Real-Time or Post Flight
  - Bandwidth for Real-Time
  - Volume (for On-Board Storage)
- Reliability
  - Mission Success
  - Vehicle Loss Rate

What is your current knowledge of UAV capabilities?

- Current Missions
- Platforms
- Availability
- Air space Restrictions
- Reliability
- C^3 Options

(What is your vision of the future?)
What is your opinion about the use of UAVs to accomplish your mission?
What missions do you foresee for UAVs over the next ten years (2004-2014)? Include dates if available

Figure I.1 – Customer Interview Form – page 1 of 2

Over the following fifteen years (2014 – 2029)? Include dates if available

What phenomena will you want to measure?

(What are your specific requirements?)
What kinds of technologies will be required to support these missions?

How will you want to measure it?

What type of scientific instrumentation will you need to make those measurements?

Over what time period and scale will you want for your measurements?

What flight conditions will you want to make measurements at? (speed, altitude, endurance)

What will be the weight, volume, and power requirements of the scientific instrumentation?

Are there special environmental requirements you will need for the instrumentation (vibration, temperature, pressurization, stability, etc.)?

What data will the scientific instrumentation require from the platform?

What type of maneuvering will you want from the platform in order to collect your measurements? (loiter, vertical profiling, etc.)

What will be the requirement for accessing the environment to be measured? Will you need viewing or sampling ports for the scientific instrumentation?

What will be the communication requirements for the instrumentation? Will real-time data monitoring be necessary? What about on-board data storage? Will uplinked control of the instrumentation be desired, and if so what type of functions will be performed?

What support equipment will be necessary for pre-flight instrumentation checkout?

Is there anything else we should know about?

Is there anyone else you think we should talk to regarding this subject?

- What other elements (horizontal or vertical) of your organization may benefit from the use of UAVs?

- Should anyone in your chain of authority be made aware of this effort?

Figure I.1 (continued) – Customer Interview Form – page 2 of 2

I.3 References

In articulating the following references, when available, a link to a website containing either the reference itself or the entire document will be given. In some cases, the materials are available to download. The references are presented in no order of preference or importance.

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