

**Rascal**

Mission Overview Document

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# Executive Summary

Rascal’s mission is to demonstrate proximity operations within a small satellite architecture, including stationkeeping, “Escape”, and rendezvous.

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# Program Introduction

Rascal is a spacecraft mission that seeks to demonstrate the performance of in-orbit proximity operations within a small spacecraft architecture. Proximity operations are defined as the performance of orbital maneuvers, such as Stationkeeping, Rendezvous, and Collision Avoidance, relative to a resident space object (As Defined in Table 1-1).

**Table 1-1. Key Proximity Operations Definitions**

|  |  |
| --- | --- |
| Proximity Operation Terms | Definition |
| Stationkeeping | Maintaining a set relative displacement between two space objects for a period of several orbits |
| Collision Avoidance | Performing an orbital maneuver that increases the relative displacement between two space objects, as to avoid on-orbit collisions and potential orbital debris creation. |
| Rendezvous | Performing an orbital maneuver that decreases the relative displacement between two space objects within a set distance for a period of several orbits. |
| Resident Space Object | Any satellite or object residing in space |

Proximity operations have been designated by the NASA Innovative Advanced Concepts (NSPIRES) program as one of many transformative ideas that will help enable new aeronautics and space systems capabilities[[1]](#footnote-1). If successful in demonstrating the performance of such operations, Rascal would act as a stepping stone to future development and refinement of the technologies and processes involved with the performance of proximity operations, potentially leading to the creation of small satellites that are capable of inspecting, or even repairing, damaged satellites or crew capsules, saving millions of dollars and man hours associated with the replacement of said systems that would normally have no cost-effective means of being repaired in-orbit.

This document serves to elaborate on the relevance and feasibility of proximity operations demonstrations for small spacecraft from historical, analytical, and operational perspectives, as well as outline the mission requirements, success criteria, and design flow-downs for the Rascal mission itself.

# Mission Relevance and Justification

## Relation to NASA Objectives

## Proximity Operation Mission History

Rendezvous and proximity operations (RPO) missions have a long history in human spaceflight dating back to the first Gemini missions. It was not until the previous decade did interest arise in approaching RPO missions with purely robotic systems. For the most part, RPO missions have been solely under the purview of NASA and the military; only recently have private companies and universities made inroads in this area. Each mission has taken a different approach to RPO and has ranged from small CubeSats to massive multi-million dollar satellites. The successes and failures of these missions have helped drive the constraints of the Rascal Mission (Discussed in Section 5.2.6). A summary of theses missions, as well as the success, cost, and lessons learned from their execution, are listed in Table 3-1.

Many previous RPO missions have been large million dollar satellites, each of which approached their mission in many different ways in an attempt to demonstrate many different RPO capabilities. Out of these missions, three were selected for more analysis based on the types of RPO capabilities that they demonstrated.

The first of these spacecraft is the Demonstration for Autonomous Rendezvous Technology (DART) mission, built by Orbital Sciences Corporation for NASA to develop and demonstrate autonomous navigation and rendezvous. Its mission involved attempting to dock with an experimental communication satellite. The primary objectives of the mission were to navigate autonomously using GPS and rendezvous using an Advanced Video Guidance Sensor. Within a few hours of launch, it was able to reach its target and experienced a malfunction as it began its approach, resulting in a soft collision with the target vehicle, which lead NASA to end the mission to find the cause of the malfunction. Though not publically released, the soft collision was likely a result of the chaser satellite approaching the target in a manner that the navigation algorithms used to control its propulsion system did not account for. This prevented the Advanced Video Guidance Sensor from switching to its fine tracking mode from its course mode, leading the chaser to think it was further from the target than it actually was, eventually causing the collision. The total cost of the mission was $98 million. The main lesson to take away from this mission is that even when a large amount of resources and money are used to develop and test a mission, the risk associated with its execution never completely goes away. A secondary lesson that can be taken from the mission is that the method of tracking relative position between two objects is complicated and prone to risk, thus making it a key point of investigation, development, and testing for any RPO mission.

The next mission that is to be discussed is Orbital Express, which was built by Boeing and Ball Aerospace and managed by the Defense Advanced Research Projects Agency*(*DARPA*)* and the Marshall Spaceflight Center. The Orbital Express mission was meant to demonstrate several servicing operations as well as rendezvous and proximity operations. It consisted of two spacecraft, with one being the target and another being the servicing module. The primary spacecraft was able to refuel and replace the batteries of the target spacecraft. The total cost of the mission was $300 million. The main lesson from this mission is that demonstration of extremely complicated RPO maneuvers is possible, but requires a large amount of resources, development time, and testing, likely more than a university-class spacecraft can achieve. Thus, it is necessary to limit the scope of Rascal mission to a level where it can actually be achieved while still being able to demonstrate RPO maneuvers that are of use to the grater aerospace community.

The final large-scale spacecraft mission that was analyzed was the Micro-satellite Technology Experiment (MiTEx) mission. This mission consisted of three spacecraft working in geostationary orbit, with one serving as an experimental satellite and the other two as inspection satellites. The inspection satellites, with masses of 225 kg each, were technology demonstration satellites capable of maneuvering in relation to other satellites and providing platforms to inspect other satellites without detection. The satellites demonstrated autonomous operations, maneuvering, and station-keeping capabilities. They were built by Lockheed Martin and Orbital Sciences and managed by DARPA. They were able to complete their mission with the experimental satellite, and then moved to inspect a failed missile detection satellite to try to find the cause of the failure. The total cost of the mission was $24.6 million. The lessons learned from this mission are similar to those learned from the Orbital Express mission, with the extra edition of the usefulness of allowing for extended satellite operations when selecting the amount of propellant to fly with an RPO mission.

More and more private institutions are starting to move into conducting RPO missions with smaller spacecraft. Currently the missions done by private institutions have been primarily proximity operations, though they still demonstrate technologies that could be used on future RPO missions.

The first of these was SNAP-1 developed by Surrey Satellite Technology Ltd and the University of Surrey. The 6 kg nanosatellite was to approach and rendezvous with Tsinghua-1, anther spacecraft that was integrated into the same launch vehicle. After launch SNAP-1 ended up in an orbit below that of Tsinghua-1 and, being relatively light, suffered more from the effects of atmospheric drag than the much heavier Tsinghua-1 microsatellite. As a result, the two spacecraft became more separated, and, at their worst, Tsinghua-1 and SNAP-1 were about 15,000 km apart. However, SNAP-1 eventually brought itself within 2000 km of Tsinghua-1 by means of propulsion maneuvers. Thus, while a true rendezvous was not achieved, SNAP-1 was able to demonstrate the agility and maneuverability of its propulsive system under automatic control. In stark contrast to the previously discussed missions, the mission cost of SNAP-1 came in at less than $1 million. This (relatively) small price-tag shows that it is possible to demonstrate proximity operations within a small spacecraft architecture. However, the quick separation between the target and chaser satellite indicate that there are large risks associated with attempting proximity operations demonstrations between two spacecraft that enter orbit with even slightly different initial conditions. In terms of the Rascal mission, it is absolutely necessary to mitigate this risk to the fullest extent possible, as its occurrence would result in the failure of the mission as a whole.

The next mission looked at was Aerocube-4, which was developed and operated by the Aerospace Corporation. It consisted of 3 1U CubeSats that each had solar panel wings that closed and opened in an attempt to alter the ballistic coefficient (Relation That Indicates the Effect of Drag on a Given Spacecraft) of each spacecraft, thus allowing for efficient formation flying (Maintenance of Small Relative Distances Between Each Spacecraft). Each satellite included three-axis attitude control to 1 degree absolute accuracy, a 0.3-square-meter deployable deorbit device, and sub-miniature reaction wheels. The satellite also carried a launch environment data logger that recorded ascent accelerations, vibration, pressure and temperature. In order to efficiently manage the formation of each sapcecraft, a new three-node automated ground system network was developed. High-precision orbit determination (OD) was made possible by a GPS receiver installed on each satellite that collected fixes on a regular basis and delivered the measurements of the satellites’ position and velocity. The ultimate cost of the mission was around $200,000. Lessons learned from this mission include the importance of knowing and recording the exact location of spacecraft conducting RPO missions, whether accomplished by position/velocity motion sensors, GPS, or ground based tracking, and that high precision formation flying (or stationkeeping) can be accomplished through the implementation of relatively simple attitude control systems.

The final mission looked at was DRAGONsat, a partnership between University of Texas-Austin and Texas A&M. It consisted of two 1U spacecraft, one developed by UT Austin (PARADIGM) and the other one developed by Texas A&M (Aggiesat2). They were each deployed at the same time, with an objective of collecting two orbits worth of GPS data to determine how far apart the spacecraft separated from each other. The mission was ultimately a success and data was collected from both satellites on the general change in relative displacement between each of the spacecraft. The mission cost around $100,000. The lessons learned from this mission include further demonstration of the reliability and usefulness of GPS data for proximity operation missions.

## Related Activity in Proximity Operations

# Mission Objectives

## Baseline Mission

## Success Criteria

# Requirements Verification

## Rationale and Taxonomy

Requirements Verification is the method of verifying that mission success has been fully met by a given mission. This mission success is determined by the ability of a mission developer’s design to meet a checklist of primary requirements that have been issued by a potential customer (Such as NASA, Boeing, the DoD, Etc). If these top-level mission requirements are not met, it is within the customer’s judgment to determine whether or not their requirements were too strict, their desired mission is too impractical, or if their selection of mission developer is at fault. If it is the latter case, it is within the potential customer’s power to part ways with the mission developer, thus making any effort that went into the development of the mission a waste of time, money, and resources.

Hence, one of the most important portions of the preliminary stages of spacecraft mission design is properly defining mission requirements. In the case of the Rascal mission, the main source of these requirements is the Team Bravo Request for Proposal (RFP). This document describes both the type of mission that is to be attempted, as well as the success criteria associated with said mission, and thus is the main driver of mission design going forward. Implicit in these requirements is the need to remotely verify their successful completion when it comes time for the actual mission; otherwise the relevance of the Rascal mission would be moot and the rationale for its launch would be non-existent. Finally, even if the Rascal mission is designed to meet all of these requirements, and can demonstrate as much, it would be completely unreasonable for said mission to take an extended amount of time to be completed. The longer a mission takes to run out, the more resources have to be utilized in its operation and the more likely that it will experience a failure before mission success can be met. Thus, mission lifetime is a key factor in defining the mission success as a whole.

From these requirements (Known as the Primary Requirements) would then come all other requirements associated with designing a successful mission. Such requirements could be as simple as stating that the spacecraft must have a particular subsystem, or as specific as stating the force required to secure a bolt on the final spacecraft. Regardless, any of such requirements form a subset of one or more of the larger requirements above it.

The representation of the various types of requirements takes the form of a matrix consisting of the definition of each requirement, the method(s) with which it will be verified, the reason that such a requirement exists, and a requirement number for future reference.

There exist four different verification methods for each requirement can be verified:

1. **Test**: Requirements that necessitate some form of testing in order to be verified. Testing includes subjecting a component or system to vibration testing, verifying the amount of delta V that can be produced by the propulsion system, conducting thermal testing on the spacecraft system to verify that it can survive an on-orbit environment, etc. Each test will be documented in a testing document, which will in turn be used to verify that a particular requirement has been met.
2. **Analysis**: Requirements that can only be verified through computational analyses and not through physical measurement or testing. Requirements that fall under this category include calculating the thermal profile of the spacecraft system, determining the expected roll rates that can be achieved with its attitude determination an control system, finding the amount of propellant necessary to perform the mission itself, etc. Each analysis will have its own document associated with it that will be used to verify the successful completion of its corresponding requirement.
3. **Demo**: Requirements that involve demonstration in order to verify their successful completion. Requirements that fall under this category include showing that deployables will not be released until some amount of time after on-orbit ejection, that inhibits successfully cut power off to the entire spacecraft, and that the satellite communications system does not transmit during dispenser integration. Each demo requirement will be verified through test demonstration documentation prior to the actual demonstration of their completion before any organization that seeks to observe
4. **Examine**: Requirements that are verified through either visual inspection or physical measurement. Requirements that fall under this category include dimension constraints associated with the spacecraft’s external structure, the total mass of the spacecraft, etc. Each examine requirement will be verified though documentation supporting that the examination has been performed.

Each requirement will have one or more of these methods associated with its verification, as indicated by an X under its corresponding verification method column.

Each requirement will also have a brief rationale section associated with it. The rationale for each requirement will either be an extension of requirements higher up in the matrix or from constraints that have been imposed on the mission as a whole, as discussed in the next section.

## Mission Constraints

Mission constraints for the Rascal mission stem from many sources, ranging from limits on the physical size of the spacecraft used to complete it, the monetary restrictions associated with the development and integration of such a spacecraft, and the risk associated with its execution. Each of these constraints and more are described in detail in the following sections and are each crucial in both restricting the scope of the Rascal mission and allowing for its successful execution.

### Launch Vehicle Integration

One of the most important (and difficult) parts of any spacecraft mission is actually getting it off of the Earth’s surface and into orbit. Regardless of the work that is done preparing and developing the mission, if it isn’t able to be integrated into one of the currently available rockets, it will have no way of reaching orbit, and thus, no way of achieving its mission goal. Thus, it is key that whichever structure is designed to protect and encapsulate the spacecraft has the dimensions and mechanical interface necessary for it to be integrated into currently available satellite adapters.

Due to the shear amount of small spacecraft that have been launched over the past few decades, standards now exist for the integration of spacecraft into pretty much any currently available launch vehicle. Thus, if a mission follows any of these standards, it will be capable of integrating into a wide variety of launch vehicles without having to make any changes whatsoever in its integration method.

The type of adapter that a particular satellite architecture that a mission follows depends on the type of satellite that is to be integrated. Currently, there exist two major satellite classifications that any particular mission falls into: nano and micro-satellites. The following sections will discuss the definitions of each of the satellites that fall under each of these categories, as well as the pros and cons associated with each type.

#### Nanosatellite Classification

Nanosatellite class spacecraft (AKA CubeSats) are those satellites that have a mass of under 1.33 kg per 10 cm x 10 cm x 10 cm volume (AKA, One Standard Unit, or 1U). This satellite classification was developed at California Polytechnic State University (Cal Poly) in 1999 as a means of standardizing small satellite architectures across the entire small satellite industry. This served to facilitate reduced costs and time associated with the development of small satellite missions, thus allowing for organizations that would have previously not been able to develop and launch small spacecraft (Such as Universities and Privately Funded Corporations) to launch scientifically significant, impactful, low-cost missions. Nanosatellites come in several different sizes, ranging from 1U to 6U. An example of a 1U nanosatellite architecture, as defined by the *CubeSat Design Specification Document, Rev 12* is shown in Figure 5-1. Though the vertical dimension of each particular configuration depends on its type, the width of any CubeSat is limited to 100 mm, thus imposing a limit on the size that a given nanosatellite can occupy.



**Figure 5-1. CubeSat 1U Architecture**

This standardization of CubeSat sizes has allowed companies such as Clyde Space, Pumpkin, Tyvak, and Astrodev to produce commercially available CubeSat electrical power systems, batteries, motherboards, operating systems, and radios that can be integrated into virtually any CubeSat system with relative ease. This in turn allows for a greater concentration of effort in designing, building, and testing those components associated with the execution of a satellite’s primary mission, as opposed to focusing on the systems that indirectly support said components. As a result, these Commercially Off the Shelf (COTS) components have greatly reduced the time and resources required to design, build, and fly a small satellite mission.

|  |  |
| --- | --- |
| http://www.cubesatlab.org/images/AstrodevHelium-100.jpg | http://www.clyde-space.com/documents/405/405-large.png |
| http://www.cubesatkit.com/images/CSK_MB_710-00484-E.jpg  **Figure 5-2. (Clockwise from Top Left) Astrodev Helium Radio, Cylde Space Electrical Power System, Pumpkin Motherboard Rev A** | |

Another advantage of following a standardized satellite architecture is that it allows for the development of standard satellite deployers, the structures that hold nanosatellites during launch and ultimately eject them into space upon reaching orbit. These deployers, such as the Poly-Picosatellite Orbital Deployer (P-POD), Nanosatellite Launch Adapter System (NLAS), Canisterized Satellite Deployer (CSD) (Each Shown in Figure 5-3), allow for a given nanosatellite design to be integrated into almost any currently available launch vehicle, making it much more likely for a given CubeSat system to get launched than a corresponding Microsatellite mission (More on that in Section 5.2.1.3).

Thus, for a CubeSat mission, the ultimate constraint on its launch vehicle integration is whether or not it can integrate into currently available deployers. Even though such deployers are similar in principal (In that they allow for the easy integration of CubeSat payloads), each deployer has different restrictions and dimensions associated with its use, as shown in Table 5-1. From this list of deployers, as well as the other constraints listed in this document, one will be selected on which to base the design of the Rascal spacecraft

|  |  |
| --- | --- |
| http://www.nasa.gov/sites/default/files/images/747975main_NLAS_CubeSat_FULL.jpg https://directory.eoportal.org/image/image_gallery?img_id=169985&t=1338091947376 |  |
| http://0.static.wix.com/media/1c8e8f_b5d6e057eccad83ef35dd9bd9797ff63.jpg_512 |  |

**Figure 5-3. (Clockwise from Top Left) NLAS, P-POD, and CSD Nanosatellite Dispensers**

**Table 5-1. CubeSat Deployer Fact Sheet**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Deployer** | **Allowable Sizes** | **Maximum Mass** | **Specifications** | **Extra Integration Requirements** |
| P-POD | 0.5U, 1U, 1.5U, 2U, 3U | 8 kg | *CubeSat Design Specifications, Rev 12* | Separation Springs |
| CSD | 3U, 6U | 12 kg | *Payload Specification for 3U, 6U, and 27U* | Clamp Tabs |
| Wallops | 3U, 6U | 12 kg | *Wallops 6U CubeSat Deployer Specifications* | Separation Springs |
| NLAS | 3U, 6U | 14 kg | Not Available (Though Based on CDS) | Not Available |
| ISIPOD | 1U,2U, 3U | 6 kg | *CubeSat Design Specifications, Rev 12* | Separation Springs |

#### Microsatellite Classification

Microsatellite class spacecraft are those that have a mass between 10 and 100 kg. Beyond this limit, an industry wide definition of what exactly constitutes a microsatellite does not exist. Thus, it is not possible to purchase standard parts for microsatellites in the same manner that can be done for CubeSats, nor do their exist standard specifications that hold true across different launch vehicles, meaning that along with having to be designed for a particular launch vehicle adapter, every microsatellite mission must be designed for a specific launch vehicle, vastly limiting such a mission’s launch opportunities.

As a reference, the key distinguishing factors between CubeSats and Microsatellites are listed in Table 5-1.

**Table 5-1. CubeSat and Microsatellite Reference Data**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Satellite Type** | **Standard Architecture** | **Weight** | **COTS Components?** | **Launch Adapters** |
| CubeSat | 1U, 1.5U, 2U, 3U, 6U | 1.33-14 kg | Yes | P-POD, NLAS, JAXA, Wallops, CSD, ISIS |
| Microsatellite | None | 10-100 kg | No | ESPA, Lightband |

### Cost

### Mission Lifetime

### Mission Success Verification

### Mission Development Experience

### Risk

## Requirements Verification Matrix

| **Requirement** | **Verification Method(s)** | | | | **Rationale** | **Requirement Designation** |
| --- | --- | --- | --- | --- | --- | --- |
| **Test** | **Analysis** | **Demo** | **Examine** |
| Primary Requirements |  |  |  |  |  |  |
| The mission will be executed by a spacecraft |  |  |  |  | RFP Requirement | RCL-RFP1 |
| The mission must be capable of demonstrating station keeping within a 50 meter sphere of a resident space object for at least 5 orbits | x | x | x |  | RFP Requirement | RCL-RFP2 |
| The mission must be capable of demonstrating a Collision Avoidance maneuver by intentionally increasing the relative distance between it and a relative space object to at least 100 meters within one orbit | x | x | x |  | RFP Requirement | RCL-RFP3 |
| The mission shall be capable of demonstrating rendezvous with by intentionally reducing the distance between it and a resident space object to at most 50 meters for at least 5 orbits | x | x | x |  | RFP Requirement | RCL-RFP4 |
| A method of verifying the successful completion of each mission requirement shall be incorporated into the spacecraft design and mission operations procedures | x | x | x |  | Mission Operations Requirement | RCL-MOP1 |
| The spacecraft mission shall be executed within 6 months of spacecraft launch | x | x | x |  | Mission Operations Requirement | RCL-MOP2 |
| Primary Sub-Requirements |  |  |  |  |  |  |
| The spacecraft must be capable of determining relative distance between it and a resident space object | x | x | x |  | RCL-MOP1 | RCL-MOP1-1 |
| The spacecraft must be capable of recording relative distance between it and a resident space object | x | x | x |  | RCL-MOP1 | RCL-MOP1-2 |
| The spacecraft must be capable of relaying relative distance between it and a resident space object to the ground | x | x | x |  | RCL-MOP1 | RCL-MOP1-3 |
| The spacecraft will utilize a Structures Subsystem | x | x | x | x | RCL-RFP1 | RCL-RFP1-STR |
| The spacecraft will utilize a Propulsion Subsystem | x | x | x | x | RCL-RFP(2-4) | RCL-RFP-PRP |
| The spacecraft will utilize a Power Subsystem | x | x | x | x | RCL-MOP2 | RCL-MOP2-PWR |
| The spacecraft will utilize an Attitude Determination and Control Subsystem | x | x | x | x | RCL-MOP1 | RCL-MOP1-ADC |
| The spacecraft will utilize a Command and Data Handling Subsystem | x | x | x | x | RCL-MOP1 | RCL-MOP1-CDH |
| The spacecraft will utilize a Communications Subsystem | x | x | x | x | RCL-MOP1 | RCL-MOP1-COM |
| Structures Requirements |  |  |  |  |  |  |
| The spacecraft will utilize the CubeSat standard architecture |  |  |  | x | Cost Constraint | RCL-STR-1 |
| The mission will consist of two 3U spacecraft |  |  |  | x | Launch Vehicle Integration Constraint | RCL-STR-2 |
| The two spacecraft must be able to integrate into the same dispenser |  |  | x |  | Risk Reduction | RCL-STR-3 |
| The two spacecraft will be conjoined for integration into dispenser | x |  | x | x | Risk Reduction | RCL-STR-4 |
| The two spacecraft will be capable of separating in orbit | x |  | x |  | RCL-RFP(2-4) | RCL-STR-5 |
| Power Requirements |  |  |  |  |  |  |
| The power subsystem will utilize an Electrical Power System to manager power distribution to each subsystem of the spacecraft |  |  |  | x | RCL-MOP2 | RCL-MOP2-PWR1 |
| The power subsystem will utilize a battery capable of powering each subsystem for the duration of the mission | x | x | x |  |  | RCL-MOP2-PWR2 |
| The power subsystem will utilize solar panels to generate a sufficient amount of power to compensate for the energy consumption of each subsystem of the spacecraft |  |  |  |  |  | RCL-MOP2-PWR3 |
| The ADC subsystem will be capable of autonomously commanding the propulsion system to perform the orbital maneuvers associated with the RFP requirements |  |  |  |  |  | RCL-MOP1-ADC1 |
| Propulsion Requirements |  |  |  |  |  |  |
| The propulsion subsystem will be capable of executing orbital maneuvers issued to it from the ADC subsystem |  |  |  |  |  | RCL-RFP-PRP1 |
| The communication subsystem will utilize a radio for transmitting data to the ground |  |  |  |  |  | RCL-MOP1-COM1 |
| A link budget will be created that ensures that the power level, frequency, and altitudes over which the spacecraft transmits data are sufficient to produce a signal to noise ratio on the ground that is greater than one |  |  |  |  |  | RCL-MOP1-COM2 |
| The Command and Data Handling subsystem will be capable of managing the operation of each subsystem of the spacecraft, as well as the communication of data between said subsystems |  |  |  |  |  | RCL-MOP1-CDH |

## Top Level Requirements

## Structures Requirements

## Power Requirements

## Attitude Determination and Control Requirements

## Propulsion Requirements

## Communication Requirements

## Command and Data Handling Requirements

# System Overview

# Subsystem Overview

## Structure

## Power

## Attitude Determination and Control

## Propulsion

## Communications

## Command and Data Handling

## Ground Operation

1. Weaver, David. "ASA Continues Implementation Of 2010 Authorization Act Program Offices, New Technology Solicitations Announced." *NASA*. NASA, 01 Mar. 2011. Web. 06 Dec. 2013. <http://www.nasa.gov/home/hqnews/2011/mar/HQ\_11-057\_Program\_Offices.html>. [↑](#footnote-ref-1)