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# Autonomous Airborne Refueling Demonstration, Phase I Flight-Test Results

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## ABSTRACT

The first phase of the Autonomous Airborne Refueling Demonstration (AARD) project was completed on August 30, 2006. The goal of this 15-month effort was to develop and flight-test a system to demonstrate an autonomous refueling engagement using the Navy style hose-and-drogue air-to-air refueling method. The prime contractor for this Defense Advanced Research Projects Agency (DARPA) sponsored program was Sierra Nevada Corporation (SNC), Sparks, Nevada. The responsible flight-test organization was the NASA Dryden Flight Research Center (DFRC), Edwards, California, which also provided the F/A-18 receiver airplane (McDonnell Douglas, now The Boeing Company, Chicago, Illinois). The B-707-300 tanker airplane (The Boeing Company) was contracted through Omega Aerial Refueling Services, Inc., Alexandria, Virginia, and the optical tracking system was contracted through OCTEC Ltd., Bracknell, Berkshire, United Kingdom.

Nine research flights were flown, testing the functionality and performance of the system in a stepwise manner, culminating in the plug attempts on the final flight. Relative position keeping was found to be very stable and accurate. The receiver aircraft was capable of following the tanker aircraft through turns while maintaining its relative position. During the last flight, six capture attempts were made, two of which were successful. The four misses demonstrated excellent characteristics, the receiver retreating from the drogue in a controlled, safe, and predictable manner that precluded contact between the drogue and the receiver aircraft. The position of the receiver aircraft when engaged and in position for refueling was found to be 5.5 to 8.5 ft low of the ideal position. The controller inputs to the F/A-18 were found to be extremely small.


## NOMENCLATURE

| | |
|---|---|
| AARD | Autonomous Airborne Refueling Demonstration |
| AMP | Automatic Mode Progression |
| DARPA | Defense Advanced Research Projects Agency |
| DFRC | Dryden Flight Research Center |
| FTE | flight test engineer |
| fwd | forward |
| GPS | global positioning system |
| HUD | head-up display |
| INS | inertial navigation system |
| PVI | pilot vehicle interface |
| $R_C$ | capture radius |
| RFCS | research flight control system |
| STNDBY | standby |
| UAV | uninhabited aerial vehicle |
| X | Longitudinal position referenced from the end of the drogue (positive forward) |

| | |
|---|---|
| $X_{CAP}$ | the capture longitudinal distance |
| $X_{MISS}$ | the miss longitudinal distance |
| Y | Lateral position referenced from the end of the drogue (positive right) |
| Z | Vertical position referenced from the end of the drogue (positive up) |

## INTRODUCTION

The long history of air-to-air refueling has demonstrated an undeniable benefit to aviation. In recent years, the emergence of uninhabited aerial vehicles (UAVs) has opened a new realm for the application of air-to-air refueling. In developing techniques for air-to-air refueling of UAVs, new missions and capabilities are expected to become available, such as the ability of a UAV to remain on station for days or weeks at a time.

One of the first steps toward automated air-to-air refueling was taken by the Autonomous Formation Flight (AFF) program; a NASA Dryden Flight Research Center (DFRC) (Edwards, California) program aimed at automating relative navigation to maintain formation flight for the purpose of reducing fuel consumption (ref. 1). This program demonstrated a lateral and vertical station-keeping capability in straight-line trajectories. Applying this concept to the task of air-to-air refueling, the Air Force Institute of Technology (Wright-Patterson Air Force Base, Ohio) and the United States Air Force Test Pilot School (Edwards Air Force Base, California) performed autonomous station-keeping between an Air Force C-12 (Beech Aircraft Corporation, now The Raytheon Company, Waltham, Massachusetts) and the Calspan (Buffalo, New York) Variable Stability Learjet LJ-25 (Swiss American Aviation Corporation, now a subsidiary of Bombardier, Montreal, Quebec, Canada) in November 2005, in straight-line trajectories and while established in a turn. Although neither airplane was equipped to perform air-to-air refueling, the program showed that a simple control system could maintain the position of the receiver airplane within the bounds necessary for air-to-air refueling using the Air Force flying boom refueling method (ref. 2).

Compared to the amount of flight research dedicated to the Air Force flying boom refueling method, only a small amount of testing has been performed using the hose-and-drogue refueling method, which is considerably more difficult than the boom receptacle refueling technique. Preliminary work toward the goal of autonomous hose-and-drogue air-to-air refueling was performed at DFRC to characterize the dynamics of the hose-and-drogue system (ref. 3). The hose-and-drogue refueling method requires the relative station-keeping capabilities of the flying boom refueling method, but additionally requires a means of cueing the receiver aircraft to the position of the free-flying drogue. The objective of the Autonomous Airborne Refueling Demonstration (AARD) program was to develop a system to perform both of these tasks to demonstrate autonomous refueling using the hose-and-drogue system.

This report highlights the first of two flight-test phases of the program, and discusses the results. Furthermore, it describes the development of the aircraft and flight systems used in the AARD program.

## AIRCRAFT AND SYSTEMS DESCRIPTIONS

The AARD program required the modification and use of three aircraft and numerous systems. This section provides a brief description of these aircraft and systems.

### The Omega Tanker Aircraft

The tanker aircraft, shown in figure 1, was contracted from Omega Aerial Refueling Services, Inc., Alexandria, Virginia. The tanker was a Boeing 707-300 (The Boeing Company, Chicago, Illinois) modified with two hose-and-drogue assemblies in the aft section of the fuselage, each slightly off the centerline of the airplane. The drogue assemblies use standard Sergeant Fletcher baskets, and only one is extended at a time.

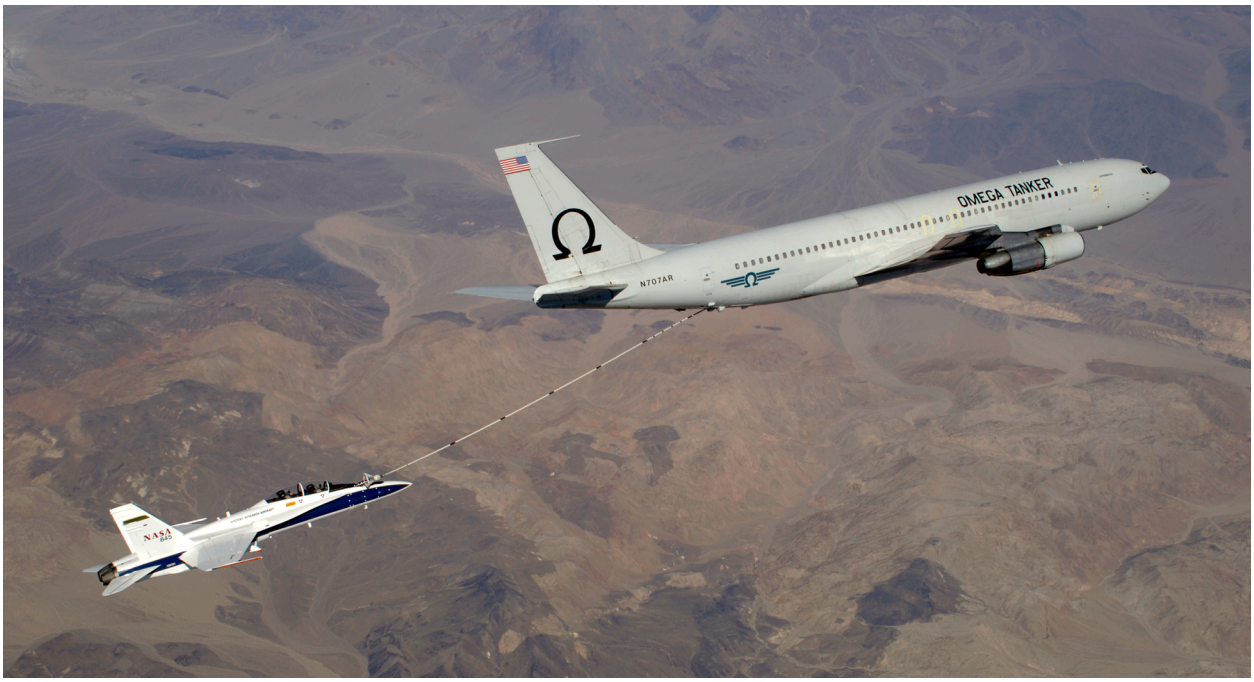


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Figure 1. The Omega tanker airplane and the F/A-18 receiver airplane.

For the purposes of the AARD program, only small modifications were made to the Omega tanker, including the addition of a global positioning system (GPS) antenna, a data-link antenna, and a computer pallet mounted on the floor of the cabin. This pallet included a PowerPC® (International Business Machines, Armonk, New York) processor interfacing to a global positioning system/inertial navigation system (GPS/INS) and a data-link modem. The sole purpose of this pallet was to measure and transmit tanker GPS/INS data to the receiver aircraft. No modifications of any kind were made to the refueling system. A notional representation of the AARD system is shown in figure 2.

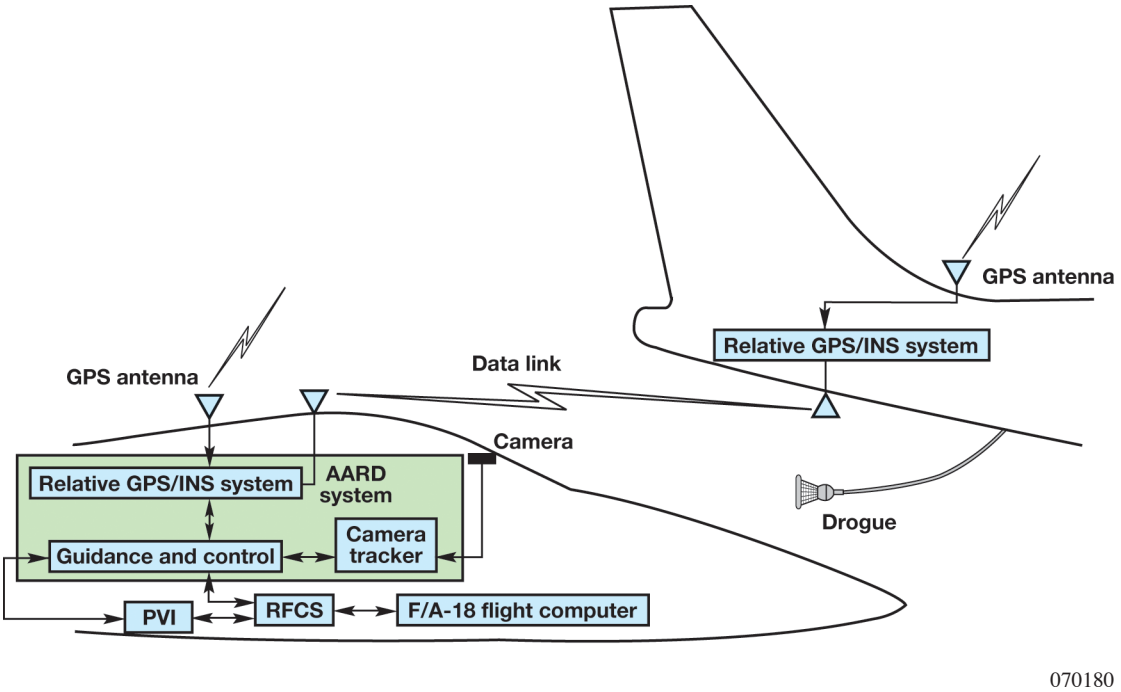


Figure 2. A notional overview of the AARD systems.

## The Surrogate Tanker Aircraft

For the purpose of testing the relative navigation and station-keeping capabilities of the system, a surrogate tanker was contracted. This was both a cost savings measure, and provided for increased scheduling flexibility. An NA-265 Sabreliner (North American Aviation, now The Boeing Company) was contracted through Flight Research, Inc., Mojave, California, and modified to have identical GPS and data-link antennae. The same computer pallet mounted in the Omega tanker was installed within the surrogate tanker aircraft before each flight.

## The Receiver Aircraft

The receiver aircraft was the DFRC Systems Research Aircraft (SRA), a preproduction F/A-18B (McDonnell Douglas, now The Boeing Company) operated by DFRC. For the purposes of this project, the SRA was used as a surrogate UAV. Takeoff, landing, and transit to and from the flight condition were flown manually. For each test point, the pilot handed control of the receiver aircraft over to the automated system. Although the SRA is not a representative UAV, it is a representative refueling vehicle for the hose-and-drogue refueling method. Not only did this refueling capability allow for the actual hardware that would be involved in this type of refueling, it also allowed for an actual refueling engagement and transfer of fuel, if the project so desired. Furthermore, it is not much of a stretch to imagine the development of an automated air-to-air refueling system for the fleet F/A-18 aircraft.

## The Research Flight Control System

The flight computer on the receiver aircraft had been previously customized to include a research flight control system (RFCS) (refs. 4 and 5) The standard F/A-18 V10.3 701E control laws had been modified to access a shared memory segment, enabling communications with the quad-redundant RFCS. Once armed and engaged, the RFCS bypasses the standard F/A-18 control laws, allowing for the execution of customized control systems. Pilot stick and rudder pedal commands would be ignored by the system. A primary benefit of using such a system is that it allows the aircraft to be flown in a standard configuration by default, enabling the RFCS only during testing. Reversion from the RFCS to the standard configuration occurs in only 1 second, and can be triggered automatically by preset limits, or by pilot command.

Practical limitations of interfacing the numerous AARD systems to the RFCS necessitated a separate flight computer, which was used for AARD sensor, navigation, guidance, and control processing. Thus, the RFCS was configured to receive external analog pitch stick, roll stick, rudder pedal, and delta throttle commands from the separate AARD flight computer, replicating the V10.3 701E F/A-18 control laws within the RFCS.

## The Autonomous Aerial Refueling Demonstration System

Designed and developed by Sierra Nevada Corporation (SNC), Sparks, Nevada, the AARD system housed the PowerPC® processor that executed the GPS/INS relative navigation blend algorithms as well as the guidance and outer-loop flight control laws. The controller contained a NovAtel, Inc. (Calgary, Alberta, Canada) GPS/INS, a data recorder, and a data-link modem to receive data from the tanker pallet, allowing the controller to compute high-accuracy relative vehicle states between the tanker and the receiver aircraft. The 1-sigma position error of the system was determined to be 0.35 ft vertically and 0.3 ft laterally using GrafMov (NovAtel, Inc.), a commercially available tool that postprocesses raw GPS data to generate truth estimates accurate to within 1–2 cm (ref. 6). The outputs of the AARD system were pilot stick, rudder pedal, and delta throttle commands. The rudder pedal command was included in the set of outputs but set to zero, as it was not expected to be necessary, and remained unused throughout the course of the program.

One useful feature of the AARD controller was the use of configuration and offset files, allowing the system to be reconfigured without recompilation of any code. A single default configuration file contained the values of key parameters within the controller, in text form. Multiple offset files contained only specific key parameters and values that would override those specified in the default configuration file. Either the default configuration file or any single offset file could be selected between test points, allowing for in-flight reconfiguration of the system.

## The Camera Tracking System

To track the motion of the drogue, a camera tracking system was integrated into the AARD system. A single camera was mounted inside the cockpit of the receiver, to the right of the head-up display (HUD). The camera was connected to a commercial off-the-shelf (COTS) OCTEC video tracking processor (OCTEC, Ltd., Bracknell, Berkshire, United Kingdom). The COTS software

was modified to meet the needs of the AARD tracking task. Figure 3 shows the view from this camera system, along with the accompanying tracking symbology. The camera tracking system processed the image and output the azimuth, elevation, and range to the drogue. The location and orientation of the camera to the body frame of the receiver was ascertained prior to first flight by using a laser theodolite. The camera tracking system was calibrated as well, by recording video of previously-surveyed stationary targets on the hangar wall. The AARD system was configured to command the camera tracking system to begin tracking at a specified step in the refueling process. The mode in which the data from the camera tracking system were incorporated into the AARD guidance calculations could be configured as well.

070181

Figure 3. The OCTEC camera tracking system image.

## The Pilot Vehicle Interface

The last component of the AARD system was the pilot vehicle interface (PVI), shown in figure 4. Designed by DFRC, the interface itself is an eight-button display, each button having the capability of displaying text on two lines of six characters per line. An RTD PC104 (RTD Embedded Technologies, Inc., State College, Pennsylvania) system running Debian GNU/Linux provided the processing and interfaces to the other systems. The button displays could be made to change in real time, and provided feedback to the flight test engineer (FTE) in the back seat. A menu system was developed to increase the functionality of the system.

070182

Figure 4. The pilot vehicle interface.

## Reference Frames and Positions

Unless specified otherwise, the reference frame used in the remainder of this report is a left-hand Cartesian system, aligned with the tanker body axes and filtered to stabilize the reference frame. The axes are defined so that X is positive forward, Y is positive toward the right wing, and Z is positive up. For the purposes of this report, the reference point of the drogue in all graphs is on the centerline of the drogue, at the end plane of the drogue feathers. The receiver position reference point is the tip of the extended refueling probe.

## Concept of Operations

The concept of operations began with the notion that the automated refueling process should mimic that of standard piloted operations. Changes would be made as necessary to accommodate the automated nature of the system. The project pilots were interviewed and involved in the original concept of operations shown in figure 5.

The process consisted of a Trail position for initial rendezvous, a Pre-Contact position 20 ft behind the drogue, and a Hold position for after drogue capture. This process was mechanized through a stepwise process, highlighted in figure 6. An automatic mode progression (AMP) was developed, which stepped through each of the modes automatically using countdown timers at each step. To allow for a build-up approach during flight-testing, a manual mode progression was implemented to disable the timers and allow the aircrew to step through each of the modes at their discretion.

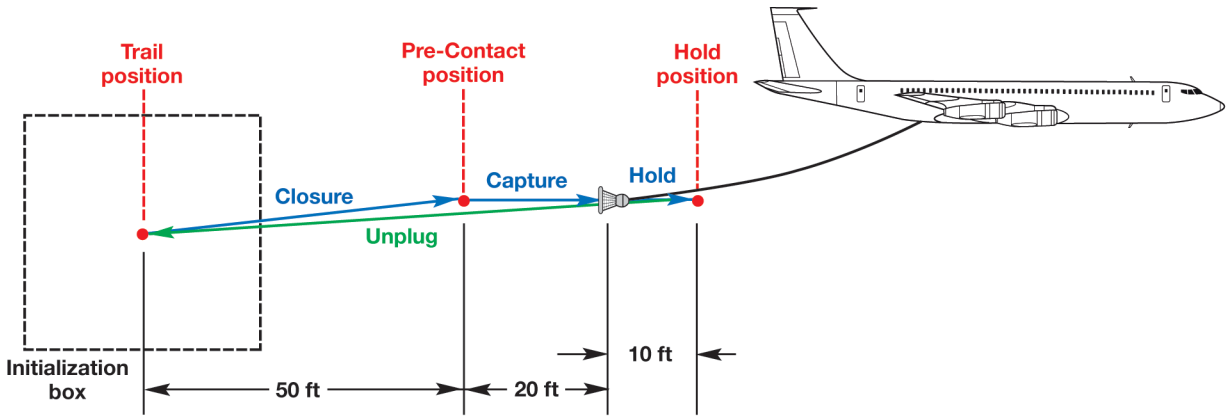


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Figure 5. The AARD refueling process.

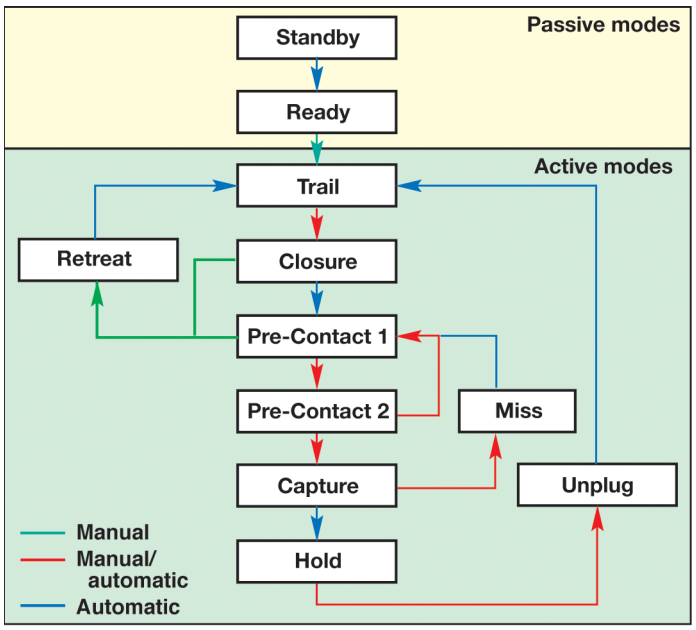


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Figure 6. The AARD controller modes.

## Standby Mode

After system power-up, the AARD controller started in Standby mode. Standby mode was a “safe” mode to prevent an inadvertent RFCS engagement before the receiver was on condition and ready to start the refueling process. At any time during the refueling process, failure detections from the AARD controller or an RFCS disengage reverted the system to this mode.

## Ready Mode

Ready mode was defined as the last mode prior to the activation of the AARD system and the subsequent transfer of control of the receiver aircraft. After the rendezvous of the tanker and the receiver, the pilot of the receiver aircraft manually maintained formation flight behind the tanker at the Trail position, which was nominally 70 ft aft, 10 ft down, and laterally aligned with the estimated drogue position. To ensure a safe and smooth transition from piloted to automated flight, a "ready box" was created around the Trail position, nominally ± 25 ft in the X, Y, and Z axes. Several conditions were required to be satisfied for the system to enter Ready mode. These requirements included verifying that the receiver aircraft was within the ready box, that the data link had been established between the receiver and the tanker, and several other system health indications. Once these conditions had been met, the system automatically transitioned into Ready mode. The pilot of the receiver airplane could then arm and engage the RFCS, and the FTE in the back seat could transition the AARD controller into the active state by selecting Trail mode.

## Trail Mode

Upon entering Trail mode, the AARD controller transitioned the receiver aircraft from its initial position (somewhere inside the Trail box) to the Trail position over a predefined length of time. Both the transition time and the ready box size were tested in the six-degree-of-freedom (6DOF) nonlinear simulation prior to flight to ensure that any transients that might occur on transition from Ready mode to Trail mode were acceptable. If in automatic mode progression, Closure mode was entered upon timeout of the Trail timer. If in manual mode progression, the receiver remained in Trail mode indefinitely, until the FTE commanded "Closure" on the PVI. While in Trail mode, the FTE could select forcing functions to initiate step or sinusoidal biases to the X, Y, or Z position commands, one at a time, for system identification purposes.

## Closure Mode

In Closure mode, the AARD controller commanded a preprogrammed closure velocity profile toward the drogue, while transitioning the commanded position of the receiver from the Trail position to the Pre-Contact position. Upon reaching the Pre-Contact position, the AARD controller automatically transitioned to Pre-Contact 1 mode. Alternatively, the FTE could command a retreat back to Trail mode while in Closure mode or in Pre-Contact 1 mode.

## Retreat Mode

Whether entering from Closure mode or Pre-Contact 1 mode, Retreat mode serves the same purpose: to transition the receiver back to the Trail position from its current position. Upon entering Retreat mode, the receiver aircraft is automatically flown from the current position to the Trail position. Once the longitudinal position reaches the Trail position, the AARD controller transitions back into Trail mode. At that point, the aircrew has the option to continue with the refueling process.

## Pre-Contact 1 Mode

The Pre-Contact 1 position was nominally located 20 ft behind, and aligned laterally and vertically with, the estimated drogue position. The AARD controller maintained the receiver's position at this location until switching to Pre-Contact 2 mode. This mode allowed the aircrew and control room time to evaluate the performance and health of the system prior to continuing. Before transitioning to Pre-Contact 2 mode, the camera tracking system must obtain a lock on the drogue. Transition to Pre-Contact 2 mode occurred either through an automated timeout, or by manual command on the PVI. As in Closure mode, the FTE could command a retreat back to Trail mode if desired.

## Pre-Contact 2 Mode

Upon switching to Pre-Contact 2 mode, the vertical and lateral positions began to track to the drogue position, as reported by the camera tracking system. The longitudinal position was held at 20 ft behind the actual drogue position. Once again, the system remained in this mode until the automated timer ran out or until commanded by the FTE to another mode. The FTE could also command a transition back to Pre-Contact 1 mode.

## Capture Mode

On entering Capture mode, the AARD controller commanded a positive longitudinal closure rate of 1.5 ft/s toward the drogue. Vertical and lateral positions continued to track to the actual drogue position, centering the probe behind the drogue. The receiver aircraft continued to drive toward the drogue until either the capture or miss criteria were met.

In the hose-and-drogue refueling process, it is not uncommon for the drogue to make contact with, and occasionally cause damage to, the receiver aircraft. Historically, damage during piloted refueling attempts has included dented skin panels, damaged pitot-static and angle-of-attack ports, cracked or broken canopies, and damage to the probe and drogue. As a result, care was taken to err on the side of safety when defining the logic of how the system would detect and handle a miss scenario.

Figure 7 represents a two-dimensional cross section of the capture criteria and miss criteria. The actual criteria can be obtained by revolving the shaded areas 180° about the x-axis. The capture radius, $R_C$, was defined as being 4 inches inside the outer ring of the drogue, which was suggested by the project pilot as a diameter that would result in a 90 percent success rate with minimal vertical and lateral velocity. Thus, $R_C$ defines a tube coaxial to the drogue. During a successful capture, the probe must remain within the green zone and transition into the blue. That is, the probe can be at any radial distance up until the miss longitudinal distance, $X_{MISS}$, is reached, after which it must remain within $R_C$ until the capture longitudinal distance, $X_{CAP}$, is reached, for a successful capture to be declared. Upon successful capture, the AARD system automatically transitions into Hold mode. Conversely, a miss is declared if the probe moves outside $R_C$ after $X_{MISS}$ has been reached and prior to reaching $X_{CAP}$. In addition to the automated miss detection, the FTE can command a manual transition into Miss mode at any time during Capture mode.

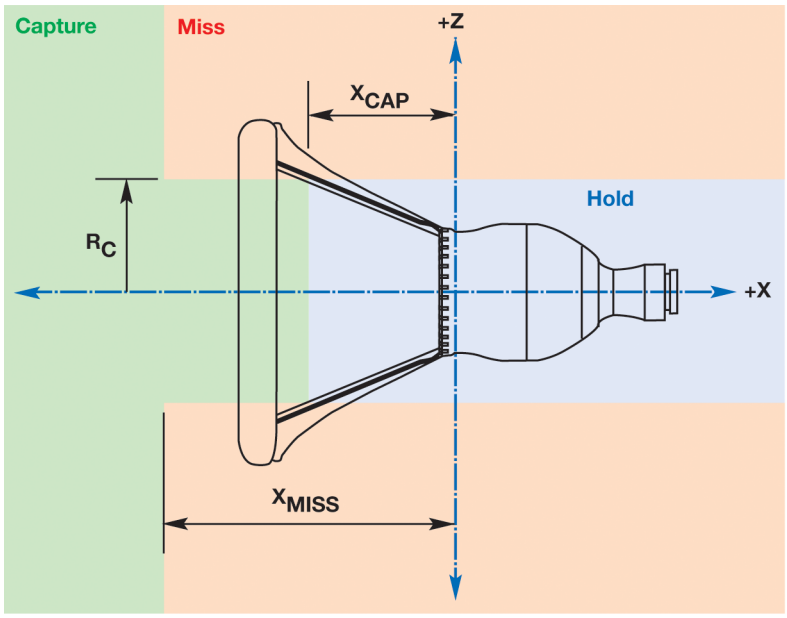


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Figure 7. The miss and capture criteria.

## Hold Mode

Upon entering Hold mode, the closure velocity of the receiver aircraft is reduced as the aircraft continues forward to the Hold position, nominally 10 ft ahead of the average drogue location. This position corresponds to the middle of the longitudinal refueling window, within which fuel transfer can occur. The camera tracking system data are faded out after entering Hold mode; at this point, the camera tracking system is no longer providing useful information because the drogue is fixed to the probe. At the same time, the vertical and horizontal positions are commanded to their Hold values, nominally set to zero, for the duration of Hold mode. The AARD system was designed to support nonzero lateral and vertical Hold positions, but this feature was not utilized in the first phase of flight tests. If in automatic mode progression, a predefined timer counts down to zero before commanding an unplug. If in manual mode progression, the receiver aircraft remains in Hold mode until the FTE selects a transition to Unplug mode on the PVI.

## Unplug Mode

The purpose of Unplug mode was to safely back out the receiver aircraft and perform an automated unplug of the drogue during the critical moments when the probe is still connected to the drogue. An unplug velocity is commanded to back the receiver aircraft away from the tanker. The receiver backs straight out until reaching the Pre-Contact longitudinal position. The commanded receiver position is then translated back to the Trail position. The system then transitions back into Trail mode, upon which it continues with the refueling process as if the receiver had just transitioned from Ready mode.

### Miss Mode

Miss mode can be entered either automatically upon detection of the miss criteria, or manually by FTE command while in Capture mode. On entering Miss mode, the closure rate is immediately reverted, and the vertical and lateral commands are frozen at the values held just prior to switching to Miss mode. By holding last commands, it was hoped to avoid tracking the large motions of the drogue that were anticipated to occur during a miss. Additionally, in the case in which the probe has made contact with the drogue, it was determined that the safest fallback would be to retreat straight back to avoid undue stress to the probe or drogue. Upon reaching the Pre-Contact 1 longitudinal position, the system transitions to Pre-Contact 1 mode. After the receiver aircraft re-stabilizes, the aircrew can continue the refueling sequence for another capture attempt in manual mode progression. When automatic mode progression was activated, the timer countdown value at Pre-Contact 1 mode was assumed to be of sufficient duration for the receiver aircraft to stabilize.

## FLIGHT-TESTING

Research flight-testing of the AARD system occurred between June 16, 2006, and August 30, 2006. A build-up approach was followed, eventually culminating in two successful autonomous refueling engagements.

### Flight-Test Objectives

The flight-test plan for the AARD project followed a buildup approach with the following objectives:

1. Verify navigation sensor data quality and operation.
2. Verify basic mode switching.
3. Verify response to step and sine commands.
4. Identify closed-loop system performance.
5. Verify basic drogue-following performance.
6. Drogue captures.

### Executed Flights

A total of 13 flights were performed in the course of the Phase I flight testing, with 9 of these flights being research flights. Table 1 lists the flights number, date, and the objective of each flight of Phase I.

Table 1. Flights and objectives.

| Actual Flights | | |
|---|---|---|
| **Flight** | **Date** | **Objective** |
| 764 | 8/4/05 | Functional check flight |
| 765 | 10/25/05 | Omega tanker airplane: camera system evaluation tests |
| 766 | 5/22/06 | Functional check flight |
| 767 | 5/24/06 | Functional check flight |
| 768 | 6/16/06 | Sabreliner surrogate tanker airplane: Mode-transition testing through Closure mode, forcing functions testing |
| 769 | 6/16/06 | Sabreliner surrogate tanker airplane: instrumentation temperature high, flight aborted |
| 770 | 6/27/06 | Sabreliner surrogate tanker airplane: mode-transition testing through Pre-Contact 1 mode, forcing functions testing; Trail mode held through a turn |
| 771 | 6/29/06 | Sabreliner surrogate tanker airplane: forcing functions testing |
| 772 | 7/11/06 | Omega tanker airplane: F/A-18 hydraulic leak, flight aborted |
| 773 | 7/18/06 | Functional check flight |
| 774 | 7/27/06 | Omega tanker airplane: left drogue hydraulic failure, three manual plugs performed, flight aborted |
| 775 | 8/17/06 | Omega tanker airplane: mode transitions through Pre-Contact 1 mode, data-link interference, flight aborted |
| 778 | 8/30/06 | Omega tanker airplane: mode transitions through a complete refueling cycle, six capture attempts with two successful captures |

Prior to the development of the AARD system, an initial F/A-18 functional check flight (Flight 764) was flown, followed by a flight behind the Omega tanker (Flight 765). The purpose of Flight 765 was to manually fly the receiver aircraft behind the tanker to record data to be used in the development and initial testing of the OCTEC camera tracking system.

Seven months later, the AARD system was ready for testing. Two F/A-18 functional check flights were flown (Flights 766 and 767), followed by four flights behind the Sabreliner surrogate tanker (Flights 768 to 771). These flights evaluated mode switching from Standby mode through Pre-Contact 1 mode. Additionally, sinusoidal and step-forcing functions were performed for system identification and to evaluate the performance of the system. During Flight 770, the receiver aircraft followed the tanker through a turn while in Trail mode, remaining stable and showing favorable handling in the turn.

The remainder of flights in the AARD program (excluding functional check flights and ferry flights) were flown behind the Omega tanker. In each flight, the primary objective was to evaluate the camera tracking system. The secondary objective of these flights was to continue mode-transition testing through Capture mode, Miss mode, Hold mode, and back to Trail mode. The first

three flights behind the Omega tanker ended prematurely because of various systems problems. In each case, the problems, though not directly related to the AARD system, prevented the camera tracking system from tracking the drogue. Consequently, the AARD system was unable to progress past Pre-Contact 1 mode on any of these flights.

The last flight of the AARD program (Flight 778) was flown on August 30, 2006. Flight activities continued from the previous flight. The problems from the previous flights did not reappear, allowing the camera tracking system to lock onto the drogue and the receiver to progress to Pre-Contact 2 mode for the first time. Mode transitions were performed in Pre-Contact 2 mode and Capture mode to ensure the capacity to fall back to previous modes or to allow complete disengagement of the system. A series of six capture attempts followed, with two successful captures, three misses, and one "false miss." In the case of the false miss, the miss criteria were violated, but as the receiver aircraft continued forward, prior to reversing its closure rate, the drogue centered itself onto the probe. Thus, had the miss criteria been less stringent, that attempt would have resulted in a successful plug.

## RESULTS

The following sections highlight three of the six capture attempts, showing a miss, a "false miss," and one successful capture. Figures depicting the remaining three capture attempts, including two misses and one successful capture, are located within the appendix.

The first capture attempt is shown in figure 8. The time signal of this figure, as well as all of the capture time histories to follow, starts just after the transition into Capture mode and ends approximately 5 s after transitioning to Miss mode or Hold mode.

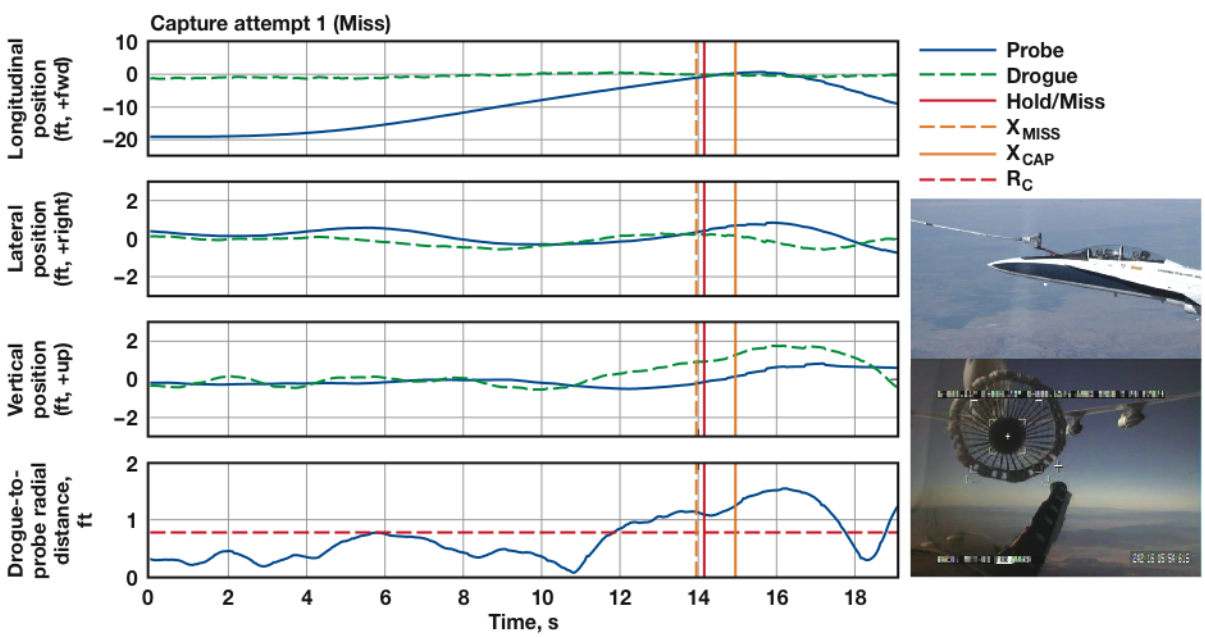


Figure 8. Capture attempt 1 positions, HUD; chase video at most forward position.

The drogue vertical position oscillates lightly about zero up until approximately 10–11 s into the time history, when the drogue is pushed upward by the forebody flow field of the receiver. Essentially, the forebody flow field refers to the flow field of the air around the nose of the receiver aircraft, which adds vertical and lateral components to the freestream air ahead of and around the nose. The forebody flow field tends to push the drogue up and to the right because of the location of the probe with respect to the centerline of the body of the receiver airplane. This drogue motion is commonly referred to by the project team as the "forebody effect." The lateral motion is not as apparent in this time history, but is more apparent in the remaining capture attempts. The initial estimate of drogue motion, based on video data from the first Omega tanker flight (Flight 765), was found to be 2 ft up and 4 ft to the right. Compared to these values, the drogue motion was relatively small, moving to peak values of 0.25 ft to the right and 1.8 ft above the average drogue location.

In the longitudinal axis, the aircraft smoothly accelerates to a constant closure rate, which is maintained until the miss is declared. Looking at the vertical tracking, it is apparent that the bandwidth is too low to adequately track the drogue. At the start of the time history, the small drogue oscillation does not result in any probe motion. This is a positive characteristic for the task, in that the controller needs only to track the gross motion of the drogue to maintain the probe within $R_C$ of the drogue center. The drogue motion caused by the forebody flow field, however, pushes the drogue upward at a rate higher than that which the controller is capable of tracking. Lateral tracking bandwidth is also too low, and additionally suffers from low damping. In the time history, the lateral response of the probe lags behind the drogue, and maintains a persistent oscillation.

Looking at the drogue-to-probe radial distance, the AARD system maintains the probe within the 0.775 ft capture radius up until shortly after the forebody effect comes into play. At the point where $X_{MISS}$ was reached, the lateral position coincidentally matched the drogue position. The vertical probe position, however, lagging behind the drogue, was far enough away from the drogue to drive the radial distance outside of $R_C$ and a miss was declared.

The longitudinal behavior of the system during the miss was excellent. The system immediately retarded the throttle to command a negative closure rate. At its furthest extent, the drogue moved 12 in ahead of the end of the drogue, the extent of which can be seen in the HUD and chase video frames in figure 8. Relative lateral and vertical motion of the drogue to the probe during the miss was very minor.

## Capture Attempt 2

After returning from Miss mode to Pre-Contact 1 mode, a second attempt was made. The results of this attempt can be seen in figure 9. The characteristics of the receiver response were similar to those in the first attempt, however, the drogue motion was noticeably different. Lateral and vertical drogue position initially oscillated about zero until the forebody flow field pushed the drogue up and to the right. The lateral drogue position moved steadily to the right to a peak value of 1.2 ft. Unlike the first capture attempt, the vertical drogue position moved quickly up to a peak value of approximately 1.7 ft before dropping back down to a steady value of approximately 1.4 ft.

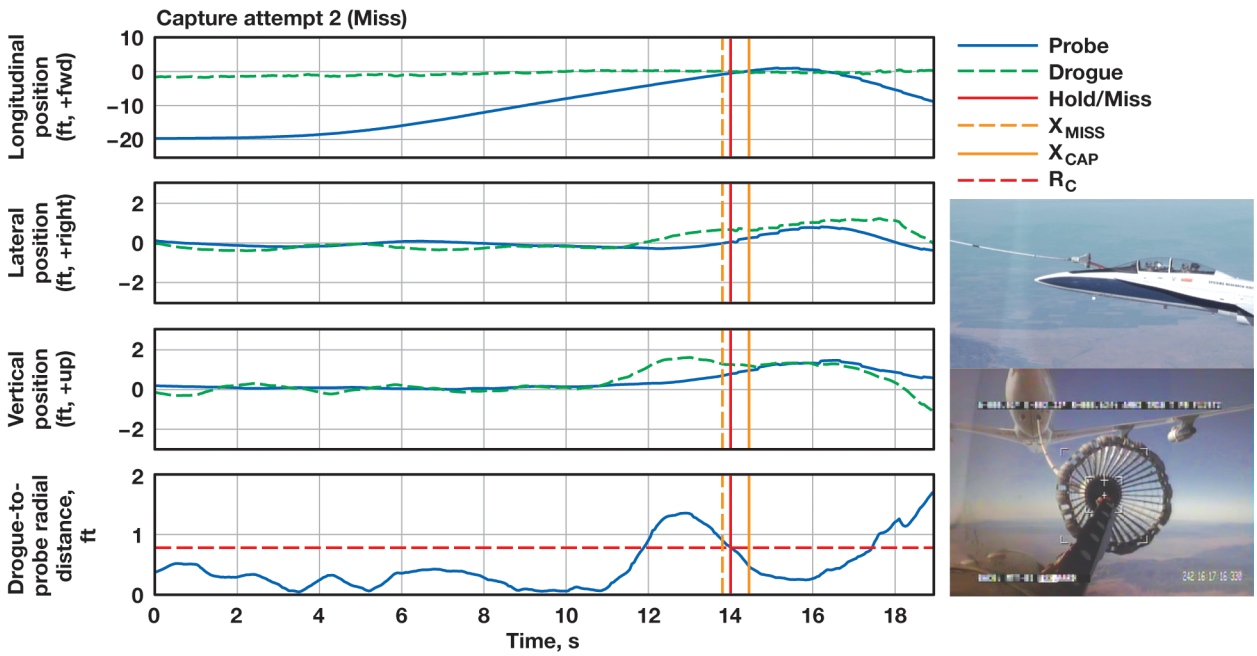


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Figure 9. Capture attempt 2 positions, HUD; chase video at most forward position.

The probe lateral position lagged behind the motion of the drogue as before, which was apparent only after the drogue started moving because of the forebody flow field. The vertical position also lagged behind the drogue motion, however, the settling of the drogue after the peak allowed the probe to catch up to the drogue at the time when the probe reached $X_{MISS}$. The plot of drogue-to-probe radial distance shows that the probe was maintained within the capture radius of the drogue up until the point where the forebody flow field began to deflect the drogue. As the AARD controller tracked the drogue, it brought the radial distance back down to below the capture radius, but not before $X_{MISS}$ had been reached. A miss was declared, commanding a negative closure rate. During slowing to reverse direction, the receiver continued forward, extending the probe tip 15 inches into the drogue and centering the drogue on the probe, as can be seen in the HUD and chase video frames of figure 9.

If the miss criteria were not so stringent, this would have been a successful plug. It must be remembered, however, that the miss criteria was defined for an estimated 90 percent success probability (when approaching the drogue with minimal vertical and lateral velocities). Although this attempt would have been successful, another attempt with contact at the same radial distance might have resulted in a miss. Additionally, it was preferable to declare a false miss rather than to declare a false plug. A miss would safely back off the receiver and transition to Pre-Contact 1 mode, from which point another attempt could be quickly repeated. A false plug detection, however, would blindly drive the receiver forward, causing a possible impact between the drogue and the receiver aircraft, forcing the pilot of the receiver aircraft to disengage the RFCS. The AARD system would then have to be re-engaged back at the Trail position, necessitating a longer downtime between capture attempts.

## Capture Attempt 6

The sixth capture attempt is shown in figure 10. Demonstrating the unpredictable nature of hose-and-drogue air-to-air refueling, the drogue motion on the sixth attempt was dissimilar to those of all the previous attempts. The lateral drogue position started at approximately 0.3 ft and was forced to the right by the forebody flow field to a steady value of 0.9 ft, where it remained through $X_{CAP}$. The vertical drogue position started at zero and slowly increased to a steady value at approximately 2 ft.

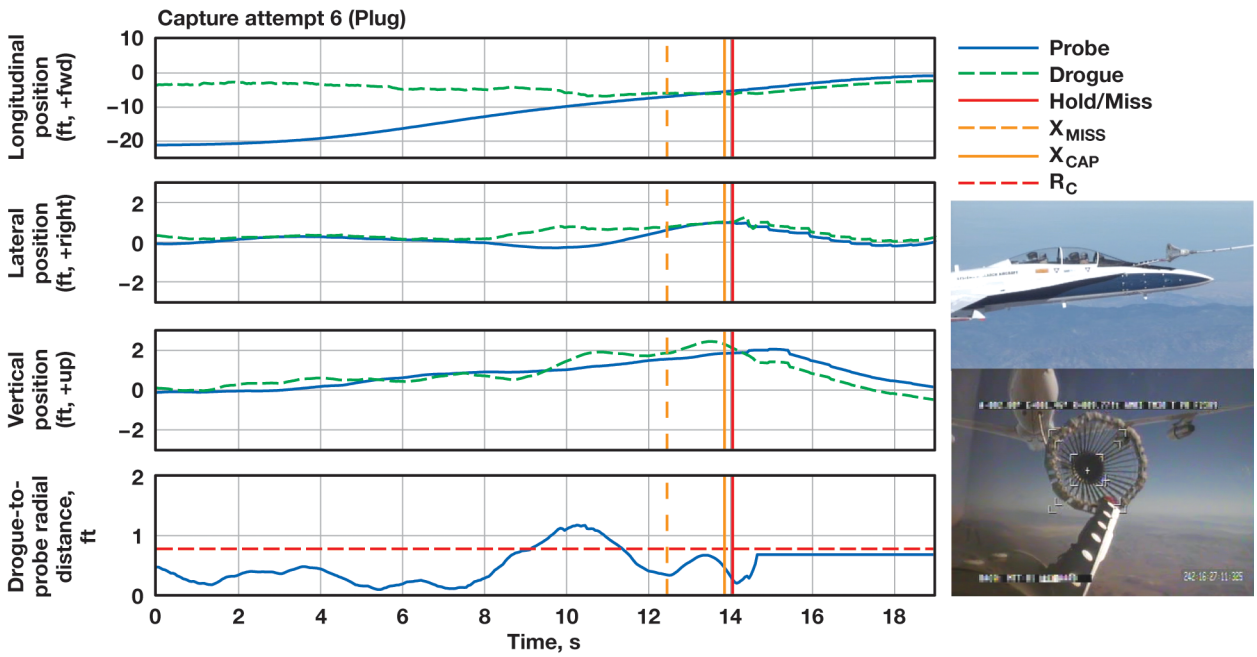


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Figure 10. Capture attempt 6, HUD; chase video at the capture longitudinal distance.

The longitudinal probe motion during the capture exhibited the same characteristics as in prior attempts. The lateral probe position matched the drogue position reasonably well at the start of the time history, but lagged behind once the drogue started to move to the right at the start of the forebody effect. The drogue deflection then leveled off, allowing the probe to catch up by the time $X_{MISS}$ was reached. Also at this time, a lateral oscillation developed which continued into Hold mode. In the case of the vertical axis, the steadily increasing drogue position was slow enough to allow the probe vertical position to keep up with the motion through to $X_{CAP}$.

The plot of the drogue-to-probe radial distance shows that the system was tracking well up until the forebody flow field began to displace the drogue. At that point, the lateral motion pushed the radial distance outside the capture radius briefly until the lateral position could be corrected by the AARD controller. By the time $X_{MISS}$ was reached, the probe was well within the capture radius. The radial distance remained within the capture radius to $X_{MISS}$, when a capture was declared, and the system transitioned into Hold mode.

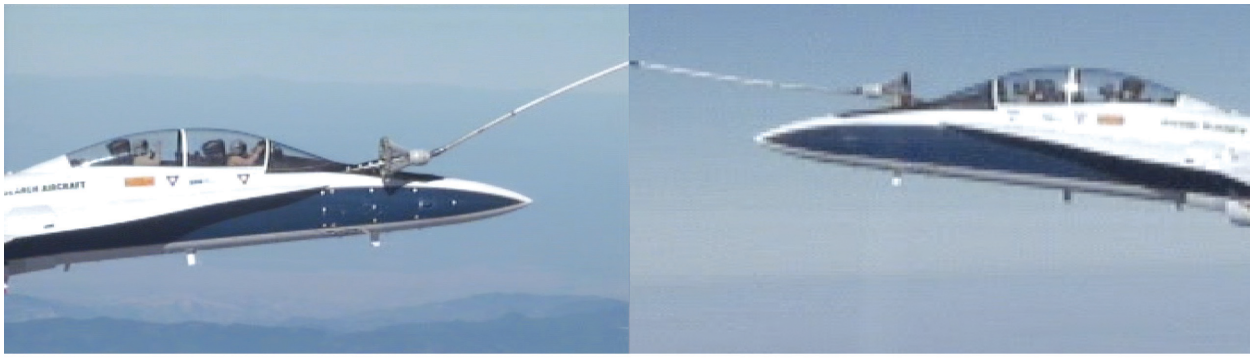
Upon entering Hold mode, the video tracker data was faded out of the guidance, transitioning back to INS/GPS-based relative position station-keeping. The receiver slowed its closure rate and continued forward for an additional 10 ft to the Hold position, maintaining the vertical and lateral positions at the average drogue location at the time of transition to Hold mode. Upon reaching the Hold position, shown in figure 11, the tanker crew reported that the extended hose length was in the middle of the refueling zone. After reaching the Hold position, the receiver aircrew commanded a transition into Unplug mode and the AARD system performed an automated unplug.

070189

Figure 11. Hold mode.

### The Receiver Position in Hold Mode

One notable difference between automated and piloted refueling engagements was the difference in vertical position during Hold mode. Figure 12 illustrates this difference, showing both an automated and a piloted engagement in the Hold position. The vertical position difference can be inferred from the difference between the angles of the hose at the connection point to the drogue.



070190

Figure 12. The Hold positions: automated (left) and piloted (right).

The longitudinal and vertical positions of the receiver during piloted and automated refueling engagements can be seen in figure 13. The two time histories are aligned such that the capture of the drogue, illustrated by the vertical green line, occurs at the same time. Since camera data were not active during the piloted plug, all measurements in figure 13 are with respect to a fixed reference point on the tanker aircraft.

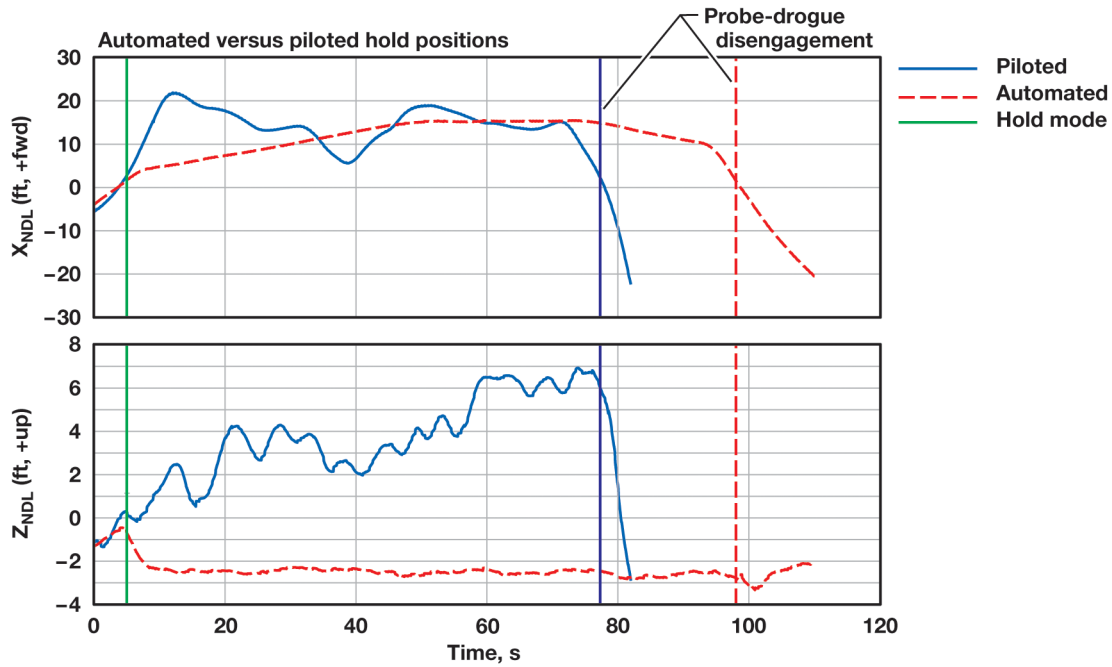



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Figure 13. The piloted and automated positions in Hold mode.

The AARD system parameters for these tests were defined such that, on transition to Hold mode, the camera data would be faded out and the receiver aircraft would transition vertically and laterally to the average drogue location. In the time history, this corresponds to a vertical position of approximately –2.5 ft. It was assumed that this position would represent the steady-state position of the drogue, and that by remaining at this position during Hold mode and the first part of Unplug mode, the radial load exerted by the hose would be minimized. As the receiver pushes the drogue straight forward and the hose retracts into the tanker, however, the angle at the hose-to-drogue connection increases, as does the vertical component of force on the drogue.

Looking at the piloted plug, the receiver moves forward and reaches the longitudinal refueling position at approximately 10 s into the time history. While at the refueling position, the vertical position varied from 3 to 6 ft on average. These data indicate that the pilot naturally compensated for the hose-length change, increasing the relative vertical position of the receiver aircraft as the hose was retracted. This was confirmed by the project pilot, who stated that the common hose-and-drogue refueling technique is to attempt to maintain the freestream hang shape of the hose while connected to the drogue. This visual picture provides both lateral and vertical position cues to the pilot, and allows for the optimal placement of the receiver during a refueling engagement.

The hose-to-drogue connection allows the drogue to pivot on the end of the hose to allow it to align with the freestream flow; however, there are limits to the amount of angular motion available. Thus, if this angle became too large, the hose would rotate the hose-to-drogue connection to its limit, imparting a torsional force on the drogue, and possibly damaging the probe or causing the drogue to pull off of the probe. The ideal Hold position, achieved in the piloted plug, naturally minimizes the hose-to-drogue connection angle. The AARD system was designed to accommodate offset Hold positions but this feature was not utilized in the first phase of the flight-test program. Future flight evaluations of the AARD controller would benefit from setting a Hold position vertical offset of approximately 5.5 to 8.5 ft above the average drogue location to account for this effect.

## General Trends

Figure 14 shows the probe-to-drogue vertical and lateral positions plotted against the probe-to-drogue longitudinal position, for all six capture attempts, from the start of Capture mode until $X_{MISS}$ was reached. Looking at the lateral positions, it can be seen that the drogue remains within approximately 1 ft of the probe for the duration of the capture attempts. The general trend for the lateral axis is that, at the beginning of closure, the drogue is either aligned or just to the left of the probe. At a probe-to-drogue distance of 8 ft, the drogue moves off to the right by 0.5 to 1.0 ft because of the forebody flow field. Just prior to reaching $X_{MISS}$ the drogue position moved back toward zero as the AARD control system positioned the probe behind the drogue.

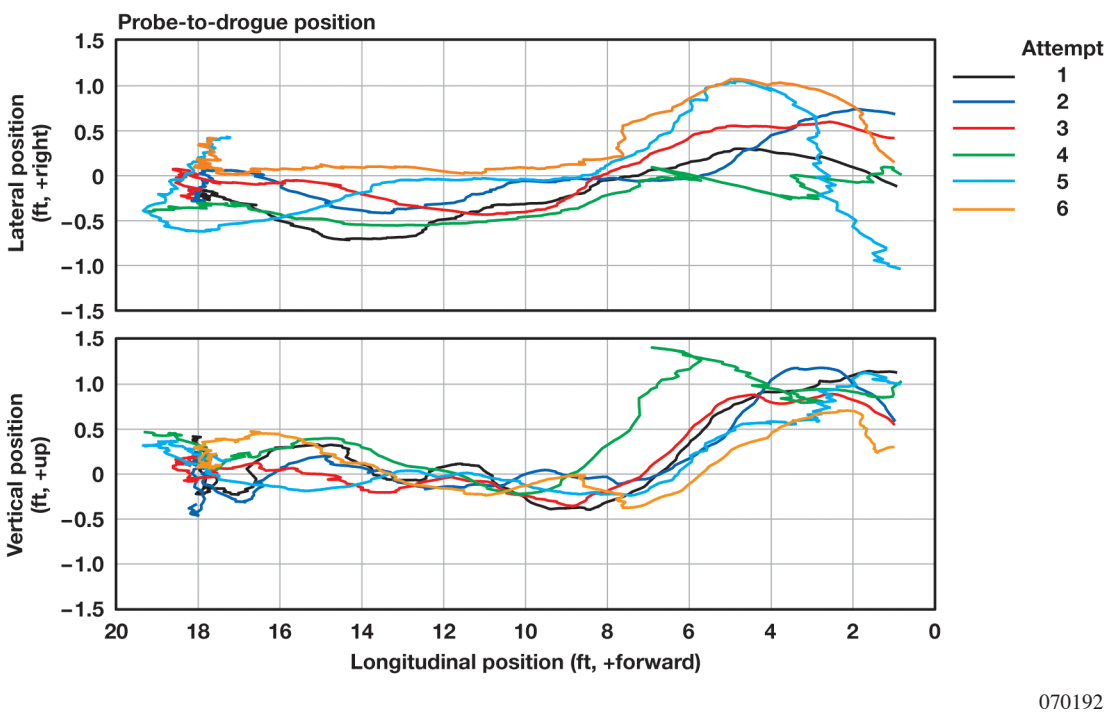


Figure 14. The probe-to-drogue position for all capture attempts.

Prior to the forebody effect, the relative vertical tracking was even better than the lateral, remaining within 0.5 ft. At a longitudinal distance of 8 ft, the drogue was pushed up to peak values around a mean value of 1.0 ft above the probe before the controller brought these values back down toward zero in the last few feet before a capture or miss.

## Stick Motion During Capture

The motion of the receiver during all phases of the refueling process was very smooth, stable, and predictable. Additionally, as was seen in some of the unsuccessful capture attempts, it was sometimes too slow to adequately perform the task. To illustrate the reason for these characteristics, plots of the pitch and roll stick position, as well as the delta throttle position, are shown in figure 15 for all six capture attempts.

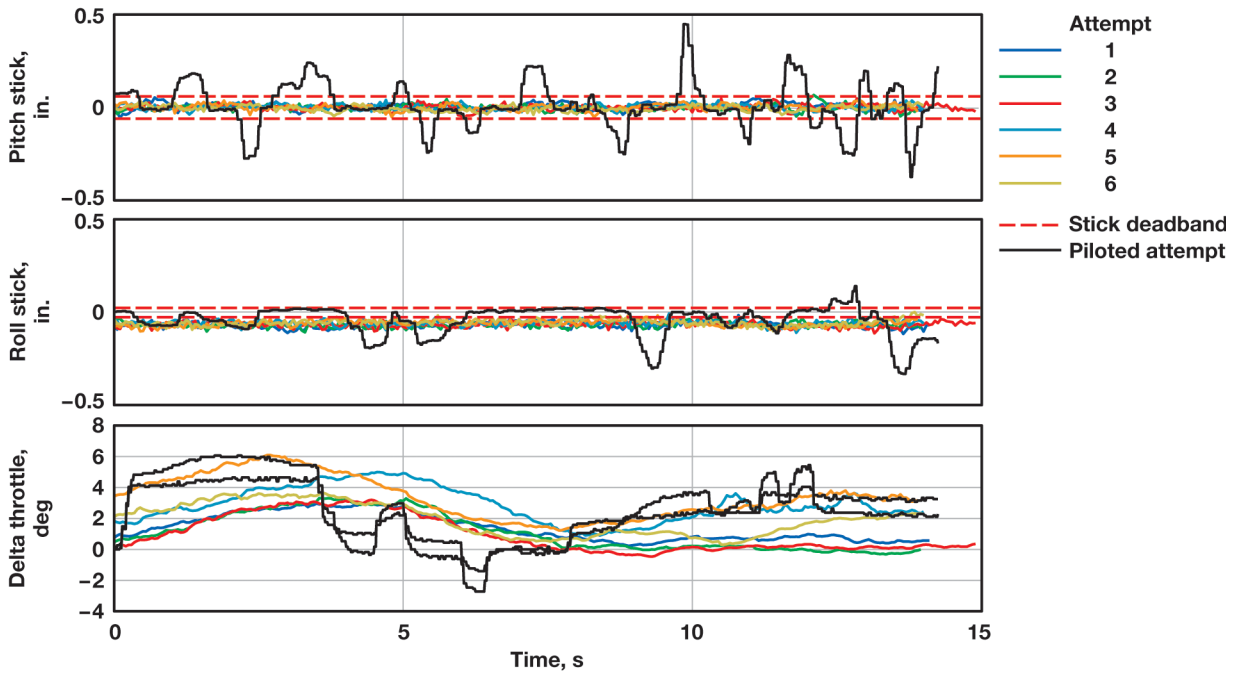


Figure 15. The stick deflections for automated and piloted capture attempts.

The stick deflections commanded by the AARD controller to the F/A-18 control system were extremely small. To provide a sense of scale, the dashed red lines represent the deadband limits of the standard F/A-18 control stick, which had been removed from the replication control laws for the purposes of the AARD program. With the exception of a single spike, all of the pitch stick commands lie within the deadband. Likewise, if the biases were removed from the roll stick signals, they too would for the most part fall within the roll stick deadband. Thus, the AARD controller commanded the receiver aircraft to successful captures using stick commands smaller than what would register on a standard F/A-18.

To get a further sense of the magnitude of the stick commands used, the stick and throttle commands from a piloted capture are shown in figure 15. Because of the precise nature of the task, and the nonlinear characteristics of the stick (at small deflections) with its mechanical and computational deadbands, the pilot commands are pulsed commands that in many cases exceed the deadband by only very small amounts. Despite this, the pilot commands were still much larger in magnitude than the automated commands. Pilot throttle commands, although not as smooth, matched the general trend of the automated throttle commands.

If the piloted commands are used as a sanity check, it can be concluded that there is still room to increase the gain of the vertical and lateral controllers while still remaining well within the extents of stick deflection used in piloted captures.

## LESSONS LEARNED

There were several lessons learned over the course of the project. These include the ramifications of an aggressive schedule, the benefits of using configuration files, and the selection of the Hold position bias.

### Aggressive Schedule

The schedule for the AARD project was very aggressive. Project start to first flight was 13.5 months, with a total project time of just 16 months. This schedule was possible because of the close working relationship between DFRC and SNC, and the limited amount of testing required of the complete system. A specific example of such working cooperation was sharing incomplete documents in draft format, which enabled work to proceed with the understanding that the information might change. Additionally, while contract obligations were fulfilled, meeting these obligations did not take precedence over the primary goal of developing, testing, and preparing the system for flight. With regard to the testing required of the system, the project used previously-developed and tested systems, and selected a flight condition that required testing to a more relaxed set of requirements. This decision saved a considerable amount of time for development and testing of the system.

### Configuration Files

Storage of critical controller parameters was accomplished by using a configuration file. This was a text file with simple parameter and value pairs. The default configuration file was read on startup of the AARD controller and stored in memory. As such, changes could be made to parameters within the AARD controller without requiring a recompilation of the code, reducing the amount of verification and validation testing required. Furthermore, offset files were used in addition to the configuration files. The offset files contain a subset of parameter definitions, which replace those of the default file when the particular offset file is loaded. Selecting the default configuration file resets back to the default values. Using this system in flight-testing was invaluable, allowing a number of system configurations to be evaluated on a single flight.

### Hold Position Bias

In the development of the concept of operations and the AARD controller, it was recognized that including the capability to bias the Hold position from the steady-state average drogue position might be advantageous. For the purpose of minimizing the complexity of the system for flight-testing, however, the offset was set to zero for all Phase I testing. During the final flight, the two successful captures showed that, at the Hold position, the receiver aircraft was approximately 5.5 to 8.5 ft below the optimal position. Future evaluation of the AARD controller would benefit from using a vertical Hold bias based on these measurements.

## CONCLUSIONS

A system was developed to perform autonomous air-to-air refueling using a hose-and-drogue system between a B-707-300 tanker aircraft (The Boeing Company, Chicago, Illinois) and an F/A-18 receiver aircraft (McDonnell Douglas, now The Boeing Company). Nine research flights were executed, progressing through a build-up approach to successful refueling engagements. Excellent relative station-keeping capabilities were demonstrated in both straight-and-level flight and in turns. Six capture attempts were performed on the last flight, resulting in two successful drogue captures and four system-declared misses. In all of the declared misses, the system safely retreated from the drogue in a controlled and predictable manner to prohibit undesired contact between the drogue and the receiver aircraft. Stick motion during capture attempts was shown to be lower than the stick deadband limits of the standard F/A-18.

# APPENDIX

## Capture Attempts 3 to 5

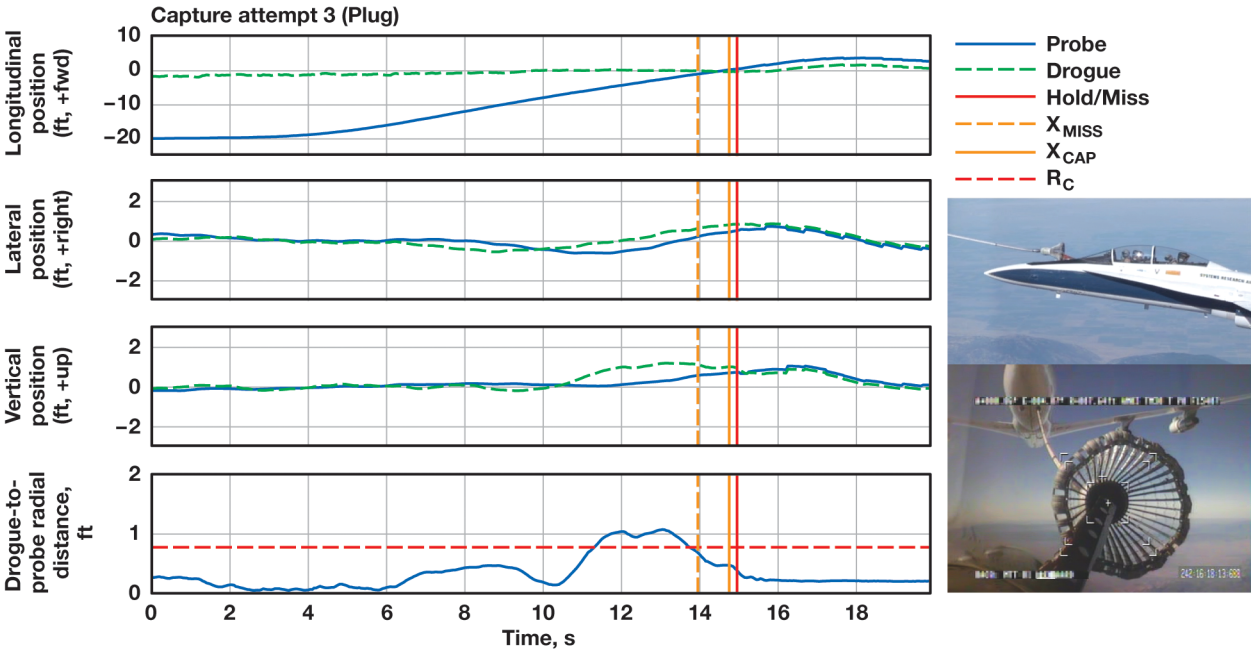


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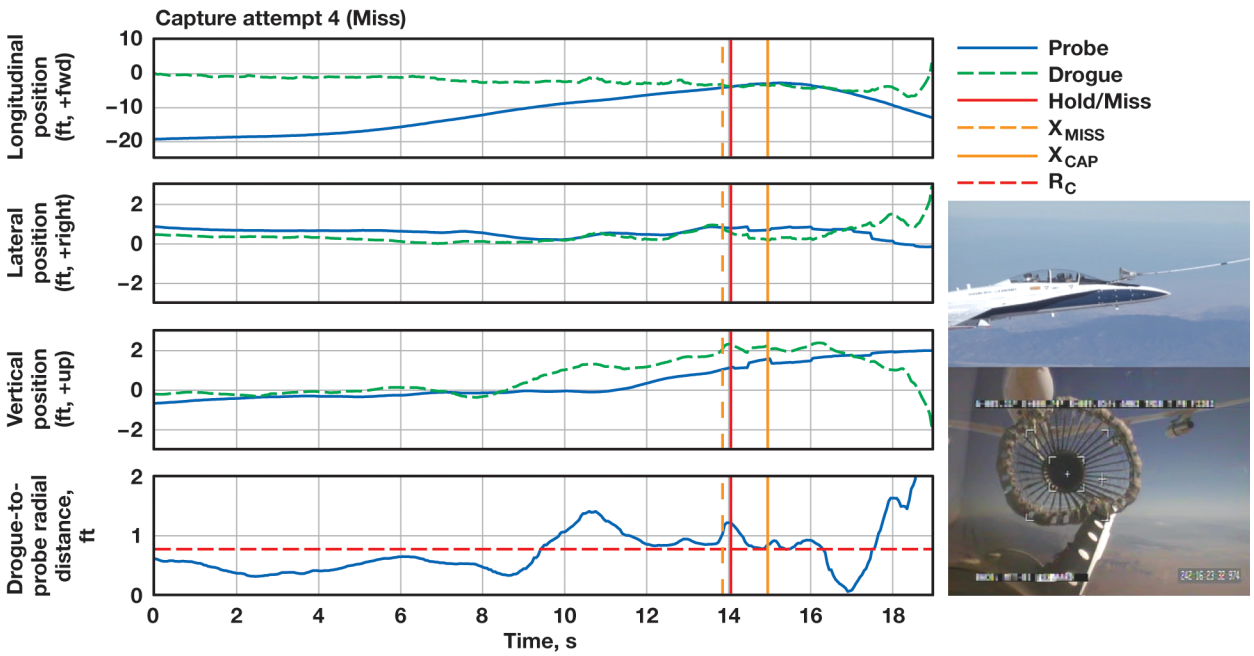
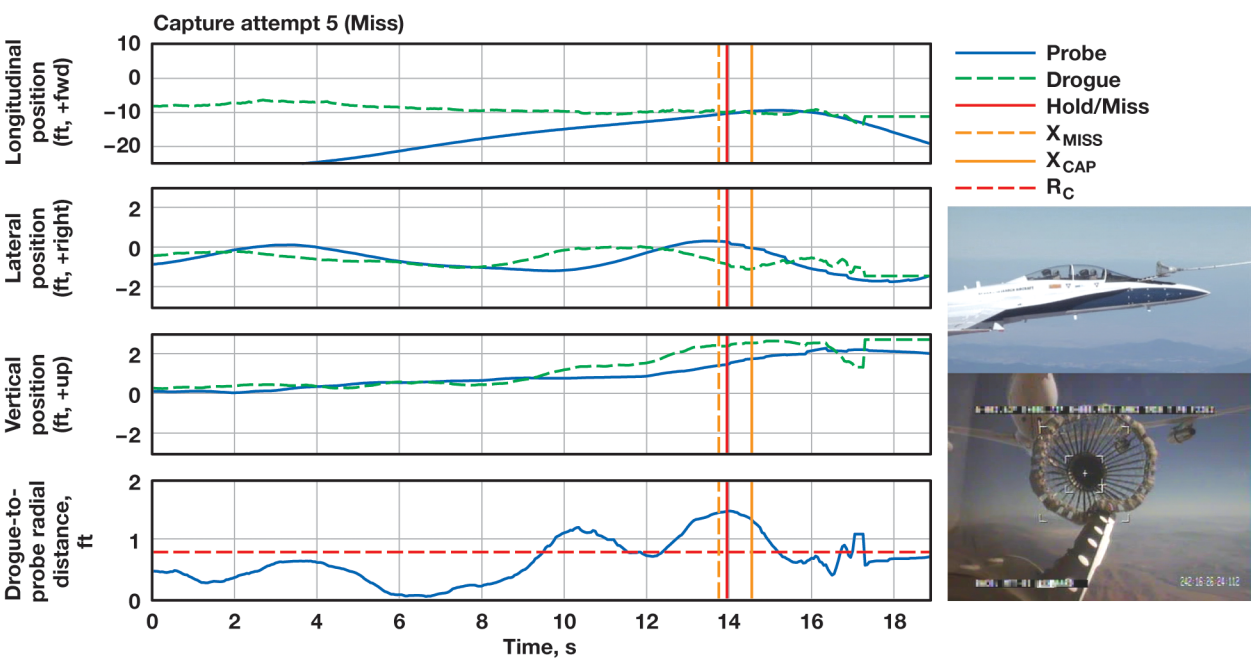
Figure A1. Capture attempt 3 (successful plug).




070195

Figure A2. Capture attempt 4 (miss).




070196

Figure A3. Capture attempt 5 (miss).

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**14. ABSTRACT**
The first phase of the Autonomous Airborne Refueling Demonstration (AARD) project was completed on August 30, 2006. The goal of this 15-month effort was to develop and flight-test a system to demonstrate an autonomous refueling engagement using the Navy style hose-and-drogue air-to-air refueling method. The prime contractor for this Defense Advanced Research Projects Agency (DARPA) sponsored program was Sierra Nevada Corporation (SNC), Sparks, Nevada. The responsible flight-test organization was the NASA Dryden Flight Research Center (DFRC), Edwards, California, which also provided the F/A-18 receiver airplane (McDonnell Douglas, now The Boeing Company, Chicago, Illinois). The B-707-300 tanker airplane (The Boeing Company) was contracted through Omega Aerial Refueling Services, Inc., Alexandria, Virginia, and the optical tracking system was contracted through OCTEC Ltd., Bracknell, Berkshire, United Kingdom. Nine research flights were flown, testing the functionality and performance of the system in a stepwise manner, culminating in the plug attempts on the final flight. Relative position keeping was found to be very stable and accurate. The receiver aircraft was capable of following the tanker aircraft through turns while maintaining its relative position. During the last flight, six capture attempts were made, two of which were successful. The four misses demonstrated excellent characteristics, the receiver retreating from the drogue in a controlled, safe, and predictable manner that precluded contact between the drogue and the receiver aircraft. The position of the receiver aircraft when engaged and in position for refueling was found to be 5.5 to 8.5 ft low of the ideal position. The controller inputs to the F/A-18 were found to be extremely small.

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AARD, Autonomous, Control, Refueling, Tanker

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