Overview: This document details the Standard Operating Procedure (SOP) for ArduPlane-based Small Unmanned Aircraft Systems (SUAS) operations performed by the Naval Postgraduate School. The content provides guidelines for safe operations of the research fleet in controlled airspace, and shall be followed at all times except as noted. References are made to additional documents specific to particular airframes, payloads, and/or operations. This document as well as the appropriate referenced articles shall be on file with the Air Safety Officer (ASO), the Aircraft Chief of Staff (ACOS), and copies will be present at all air operations. All personnel directly involved with the operation of the aircraft will be familiar with the content of this document, and will review the content on a regular basis in order to ensure that it is current, and sufficiently details the scope of operations. It is considered to be a living document, and should be updated as new issues arise. Please contact Dr. Timothy Chung (thchung@nps.edu) with questions or concerns.

1.0 Personnel Requirements: Currently all NPS ArduPlane-based SUAS are catapult assisted autonomous, non-catapult assisted autonomous, semiautonomous, or manual take-off. Landing is autonomous, semiautonomous, or manual. Minimum personnel requirements for manual operations include at least one pilot and at least one operator. Semiautonomous and fully autonomous operations require either a pilot and an operator, or two operators. The purpose of the research the ArduPlane supports is to gradually increase the number of planes in the sky until we are performing simulated combat with 100 planes in the air (this requires acrobatic maneuvers). This process will be gradual and we will begin by flying 2 planes at a time and working up from there. After a sufficient number of planes are confidently placed in the air we will begin to more dependent on aircraft autonomy and less upon a pilot. Once this is the case flight operations will need to be performed a safe distance from all non-essential personnel.

For experiments that involve more than one aircraft flown simultaneously, an additional operator or a technician is required. In scenarios involving more than 20 planes, additional technicians may be required to load planes onto catapults or retrieve planes that have arrived at the landing area.

1.1 Designations

1.1.1 Pilot: The pilot is the only individual with hands-on, real-time (stick-to-surface) control of the asset. The pilot typically has control of the asset during take-off, landing and any emergency response. The pilot is responsible for determining if
the asset is able to fly, and if the conditions are suitable for safe flight. Note that for increasing numbers of planes we are more dependent on the Operator than the Pilot.

1.1.2 **Operator:** An operator is an individual tasked with controlling the asset through the GCS during the autonomous flight (during multi-UAS operations there are typically no manual flight segments). The operator is responsible for ensuring that all safety protocols as specified in this document and the accompanying IFC(s) are followed during the autonomous flight segment. The operator is responsible for initiating emergency response procedures until such time as the control of the asset is handed off to a Pilot (should that need arise).

1.1.3 **Technician:** An individual tasked with aiding the pilot and/or operator during both the manual and autonomous flight segments. They also assist during loading of aircraft onto catapult and retrieval of aircraft following autonomous landings.

1.2 **Training**

1.2.1 **Pilot:** The pilot is required to be proficient in the radio-controlled piloting of similar type aircraft. The pilot must also be familiar with the Ground Control Station (GCS) software, and be able to determine system health, modify flight trajectories, request Return to Base (RTB), and terminate flight. The pilot must also be familiar with aircraft setup, pre-flight procedures and routine aircraft maintenance.

1.2.2 **Operator:** The operator is required to have advanced knowledge of the GCS software. In addition to the GCS requirements for the pilot, the operator must be knowledgeable on system setup, calibration, and tuning. They must be experienced in dealing with system malfunctions while in flight, to include C2-failure, GPS failure, motor failure, and GCS hardware and/or software failure.

1.2.3 **Technician:** The technician should have basic knowledge of the GCS hardware/software at the same level as the pilot. They must also have basic knowledge of aircraft assembly and pre-flight operations. They will need to assist the pilot during launch and recovery of the asset(s), and should be able to assist the operator as needed.
2.0 **Flight Operations:** All flight operations are carried out in controlled airspace. A request for permission from the acting airboss will be made before any procedural launch and recovery, and in the event of an emergency. The airboss is in direct communications with range control, and will relay the information as required.

At formal events where multiple aircraft are sharing the airspace, the airboss will establish airspace boundaries for each group of operators prior to any flights, and will monitor and adjust these boundaries as needed during the event. The airboss or a dedicated frequency manager will insure sufficient deconfliction for all participants at the event.

2.1 **Pre-Flight Checks:** Each aircraft type will have a type-specific pre-flight checklists and procedures. The pre-flight checklist serves as the flight-log while at the event, and saved for later archiving in the flight database. Every flight must have a pre-flight checklist filled out. The checklist has components which must be verified by the pilot, and others that must be verified by the operator. Some critical components require verification by both.

The pre-flight checklist covers assembly of the asset as well as system checks. The system checks will include verification of battery voltages, GPS/INS health (motor running), control surface functions (sign, limits, and linearity), propeller state, motor performance, and radio link health (requires a range check for each asset at least once per day or if the RF environment is known to have changed since the previous range check).

The Center-of-Gravity (CG) of all aircraft must be verified in the lab environment prior to departure to the airfield, with all payload components installed during a formal weight and balance procedure. The CGs of all aircraft are fixed by type, regardless of what payload they are carrying. This keeps the longitudinal gains in the autopilot constant, and handling qualities as close as possible.

Only fully charged batteries may be loaded into the aircraft. In aircraft that use multiple packs in series or in parallel, the packs are required to remain as a pair throughout their life in order to keep their drain-rate as consistent as possible. All battery use must be logged in the checklist, and batteries that show any anomaly must be disposed of, and the anomaly must be logged in the checklist. All other battery procedures must comply with the NPS Lithium SOP, as accepted by NOSSA.

2.2 **Range-Checks:** For all ArduPlane-based systems the range check will consist of operating both radios (GCS and aircraft) at full power, placing the asset 100m from the GCS antenna, and attenuating the signal on the GCS-side by 20dB and 30dB. With 20dB of attenuation the RSSI reported in the GCS must be greater than or equal to 70, and the link (percent packet throughput) must be at least 70%. During a typical range test, the pilot stands with the aircraft and the operator or technician moves the control surfaces in a slow, predictable manner to load the link with additional, time-critical data, allowing the pilot to visually inspect packet loss through control surface stutter. In flight experiments involving multiple assets, individual range checks for each vehicle must be performed, with other vehicles in the mission powered down.
when not being range-checked. Aircraft near each other or near the GCS will swamp each other and corrupt the range check.

Range checks will become prohibitively difficult as the number of planes to be launched simultaneously increases. When large numbers of planes (greater than 10) are to fly simultaneously the range checks will be automated.

2.3 **Flight Preparation:** For initial missions involving 5 or fewer planes operating simultaneously, the operator will establish a local flight path, a takeoff waypoint, a Com-Failure (CF) waypoint, and a landing waypoint prior to launch. All will be within any airspace constraints provided by the airboss (lat/long/alt). The takeoff and CF waypoints will be an orbit point, near, but not over the GCS or cantonment area. The landing waypoint will be on the ground and will also not be located in the GCS or cantonment area.

After sufficient testing has been done with 5 or fewer planes on the autopilot, planes will autonomously determine takeoff waypoints that are not over the GCS nor cantonment area and loiter until they receive instruction to commence a simulation combat engagement. We will begin with swarms of 2 planes and gradually increase that number as we become comfortable with our control systems. A common CF area (not over the GCS nor cantonment areas) is established for all planes and they autonomously perform airspace deconfliction. Planes will be given a common landing area that is not near the GCS nor cantonment area. Planes are rugged enough that it is not a concern if they land on top of each other.

Prior to flight, the pilot and/or operator must confirm that surface calibration and limits are correct. The operator must confirm that the avionics coordinate system and system degradation settings are correct, in particular, the com and GPS failure handling. The operator must also confirm that the GCS is configured for catapult launch prior to sending a technician to place the plane on the catapult.

The air sensor must be zeroed before every flight. This is done by ensuring the plane is started with the Pitot-static tube in a wind free environment. Then, velocity readings br around +/- 2m/s. The altitude given by GPS and baro-pressure are verified after GPS has converged.

The pilot, operator, or technician must check all surfaces for correct direction, limits and smooth, monotonic travel using a flight console such as a Spektrum 8 channel transmitter.

2.4 **Flight**

2.4.1 **Take-off:** Though several airframe manufacturers recommend hand launching aircraft, all NPS ArduPlane-based SUAS uses rail and/or catapult assisted autonomous launch. We feel hand launching presents an unacceptable risk of exposing personnel to a spinning propeller. Wind speed/direction must be in accordance with type-specific limits. Motor run-up must be done with the aircraft pointed away from the flight line, with no personnel in the plane of the propeller
nor on the side of the plane where the propeller is running. Non-participating observers will be kept clear of the flight line during takeoff. Take-off will be done into the wind. After take-off, the operator and pilot monitors flight. A few autonomous navigation waypoints should flown to verify system stability. Should any unexpected maneuvers occur, the pilot takes manual control flies to a safe altitude and autopilot operations can be reattempted. Should the autopilot continue to misbehave, the plane is manually landed by the pilot. Note, the pilot’s control transmitter has a switch that selects manual, semiautonomous, or autonomous flight at the discretion of the pilot. The operator has similar controls at the GCS and in multi-aircraft missions, the operator selects which aircraft the pilot console maps to, so tight coordination between pilot and operator is required if manual intervention becomes necessary. The take-off time will be recorded in the check-list.

We anticipate reaching a point within the next year where near-simultaneous takeoffs will be necessary. This will slightly increase the risk of failed takeoffs. Simultaneous takeoffs will be placed at a greater distance from non-essential personnel due to mitigate this risk. A failed takeoff likely results in a plane failing to achieve lift at launch. As the planes are styrofoam and we are flying in control air- and ground-space we feel that a failed takeoff does not present a substantial safety risk.

2.4.2 Autonomous Flight: The operator can alter waypoint locations during flight, or add new way-paths, as long as they do not violate current airspace constraints. Additional navigation commands may be passed to the autopilot through the payload computer onboard the aircraft, but must also be bound by airspace constraints, and must be cancellable from the GCS at anytime. Software aboard the autopilot handles communications failure and GPS-failure.

Secondary control is defined as any set of algorithms carried out by an onboard computer that are used to supplement the autopilot during autonomous flight, such as for swarming, formation, or combat. The secondary controller has the capability to take complete control of flight-critical components of the autopilot in order to most efficiently support its intended purpose. The secondary controller must include a failsafe that will allow the operator to revert to primary autopilot control in case the system enters an unstable state.

The pilot does not intervene during the autonomous flight segment except in an emergency (see later sections of this document and RCC 232-99 questionnaires for specific airframes for emergency and failure mode conditions). In a multi-aircraft mission, the pilot cannot take manual control of any asset without first receiving confirmation from the operator as to which asset the pilot is to take, and must have clear knowledge as to which asset it is, and what its state is.

Communication link issues may require a higher altitude for flights further from the airfield, but must remain within the approved airspace. If the operator detects that a Return-To-Base (RTB) event was initiated by one or more faults, the operator may redirect the aircraft back to the mission after verifying system health (C2, GPS, RPM).
2.4.3 **Landing:** All NPS ArduPlane-based aircraft can be autonomously, semi-autonomously, or manually landed. Typically, after receiving authorization from the airboss, the operator sends the aircraft to the CF waypoint or a suitable orbit point, and lowers the altitude to a comfortable altitude for autonomous landing or for pilot hand-off. In the case of manual landing, the pilot should confirm that the proper model is selected in the pilot console, and the pilot may take control when he is comfortable with the location and attitude of the aircraft. Ideally, landing is done into the wind, though landings at cross winds or even tail winds are possible if landing in order to clear the airfield or for an emergency landing. The airframe is resilient to hard landings.

In the case of autonomous landing (our primary landing method), the planes descend in a circular pattern until an altitude is reached in which they enter “final approach” and glide to the ground. In all autonomous landing cases the landing waypoint will be placed a safe distance from cantonment areas.

Each aircraft will perform an autonomous landing if total battery power drawn drops below 3.3 volts per cell.

2.5 **Post Flight:** Immediately upon landing, the battery voltages and landing time should be recorded in the check-list before system shutdown. Batteries should be removed, but not charged unless they will be used again within 24 hours. Any battery that is to be recharged for same day use should cool before being recharged. *Never charge a hot battery!*

Any particular remarks with the flight or flight hardware should be recorded in the checklist for possible future actions. If the landing was rough, a quick evaluation of the airframe should be done.

2.6 **Degraded System Handling:** ArduPlane software provides several rules for handling system degradation. Essentially there are events that will trigger an RTB (fly to the CF waypoint), and others that will terminate flight. Both the events for each and the definition for each are user-definable.

2.6.1 **C2 failure:** If the C2 link is degraded for 20 seconds or more, then the aircraft autonomously initiates RTB. If the link returns, the operator can either redirect the aircraft to return to the mission or let it RTB at their discretion. Usually this occurs when the range is too great for the altitude, so the operator may wish to climb higher before sending the aircraft back (constrained by airspace bounds).

If C2 link is degraded for more than 120 seconds the aircraft performs an autonomous landing at the landing point determined during flight preparation.

2.6.2 **GPS failure:** If GPS fails for 5 seconds (defined by no 3D solution, 4-sats or less), the aircraft begins circling, attempting to regain GPS link. If GPS remains out for 15 more seconds, the plane performs an immediate emergency autonomous landing and does not attempt to return to the landing waypoint. This is a precautionary step for safety and containment. If the aircraft is within visual
range of the pilot, and the primary C2 is good, the pilot may take control and land the aircraft manually.

2.6.3 Geofence: All NPS ArduPlane-based aircraft have a geofence built into the autopilot. The fence is within a 100m buffer inside the actual airspace boundaries. Most missions use a much smaller bounding box, in particular if other, non-participatory aircraft are flying nearby. Breaking the geofence boundary currently initiates an RTB.

3.0 Aircraft Limitations

3.1 Zephyr II
Limited provided in separate document: UAS Data Sheet: Zephyr II

3.2 Unicorn
Limits provided in separate documents: UAS Data Sheet: Unicorn 60, UAS Data Sheet: Unicorn 72

4.0 Range Limits

4.1 Restricted airspace: Flight operations are carried out in military restricted airspace.

4.2 Containment: As described in previous sections, range limits are enforced electronically through the geofence and other failsafes on the aircraft. The 100m buffer inside the actual airspace bounds serves as the electronic fence. Penetrating the buffer will invoke a return to the CF waypoint.