AUVSI 2007 SPAD Paper (Poster Session)

Conference:	Association for Unmanned Vehicle Systems International (AUVSI) Unmanned Systems North America 2007,
Date:	August 6-9
Location:	Washington DC Convention Center
Segment:	Air
Category:	Payloads and Missions

"Design and Test of a Sonobuoy Precision Aerial Delivery (SPAD) UAV System"

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A Sonobuoy Precision Aerial Delivery (SPAD) UAV glider system that enables GPS-controlled placement of antisubmarine warfare acoustic sensors has been developed. Unlike the current placement method, which deploys the sonobuoy via uncontrolled parachute decent, the unpowered SPAD provides 27 mile stand-off range and precise GPS-guided sensor placement to enhance signal processing accuracy. SPAD is designed to conform to existing launch tube geometry which enables use of legacy sensors (sonobuoys) and infrastructure (launchers and launch aircraft). This constraint has significant influence on the air vehicle design. SPAD's flight path is programmed aboard the launch aircraft and SPAD is then tube-launched over a wide range of speeds and altitudes up to 30,000 feet. Wings and unique grid fin control surfaces deploy after launch and the vehicle flies a prescribed flight plan down to a low altitude, whereupon the sonobuoy payload ejects from the SPAD. The sonobuoy enters the water after a brief parachute decent to deploy hydrophones up to a 1000' depth. The launch tube form factor constraints, high payload mass, Cartridge Actuated Device (CAD) explosive launch from a high speed aircraft, deployable wings, and compact grid fins control surfaces were challenging design features. Significant wind tunnel testing was conducted and is described. Alternative payloads are also currently under development and are summarized.

Mission Needs

Traditional antisubmarine warfare (ASW) features the use of air-launched sonobuoys such as shown in Figure 1. These devices, initially developed during World War II, are disposable acoustic sensors packaged to be tube-launched from aircraft at altitudes from 200 to 30,000 feet. Upon ejection from the launch aircraft, a small parachute deploys, retarding the velocity of the sonobuoy canister and orienting it to near vertical before it enters the water. Immediately upon water entry, the sonobuoy activates and deploys one or more hydrophones and other sensors to as much as 1,000 feet below the surface, connected to an RF transceiver that floats on the surface. These devices are preprogrammed to transmit data to the launch aircraft from 30 minutes to 8 hours, using up to 100 data channels, before self-scuttling.

Figure 1 – Sonobuoy launched from P3 Orion aircraft

Sonobuoys are often deployed in a grid to assist in the detection and tracking of targets of interest. As a disposable sensor, large numbers of sonobuoys have been produced and are used. Approximately 7,000,000 sonobuoys have been produced in the West, and the US Navy procures between 65,000 to 145,000 units per year at unit prices of only $250 to $1000.[1] Given these volumes and price targets, sonobuoy suppliers have perfected designs that combine low cost, high volume features with relatively sophisticated operating requirements.

Improvements are sought in two aspects of sonobuoy operation. First, it is desirable to deploy sonobuoys that have significant stand-off range. This permits the launch aircraft to deploy sonobuoy sensors without flying over potentially hostile areas, and without expending significant fuel and time for low level launch. The Navy is actively operating in regions such as the Straits of Hormuz, where operations are limited due to airspace restrictions.

Second, it is desirable to attain precision placement of the acoustic sensors in the water to improve the location accuracy calculated from the sensor grid. While winds aloft are used to calculate the Computed Air Release Point (CARP) to improve water placement accuracy, the wind data is not always accurate, and the circular error probability (CEP) for sonobuoys launched at high altitude can be hundreds of meters.

Both stand off range and precision placement are becoming increasingly important as the US Navy shifts its focus from blue water engagements to littoral operations. Furthermore, potential adversaries have acquired and operate increasingly sophisticated diesel submarines whose movements are of great interest. Potentially hostile nations, other than the former Soviet Union, currently operate more than 150

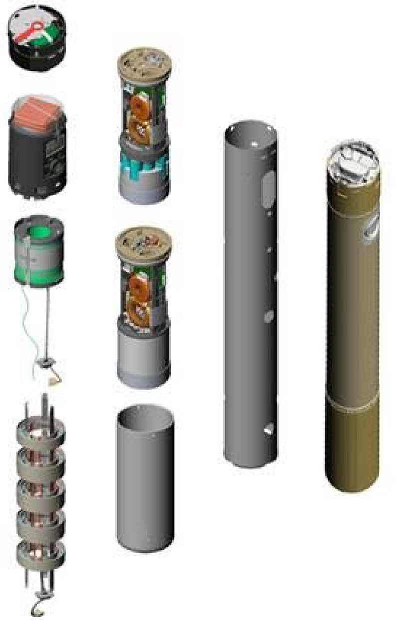

Figure 2 – Expendable sonobuoys comprise many system elements for air and water deployment

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[1] Navy P-1 Budget Item Justification, Navy, Other Procurement, B.A.3 Aviation Support Equipment, Sonobuoys, All Types, February 2003

submarines, of which 45 are non-nuclear and modern design. An additional 45 submarines are on order, and by 2030 it is projected that three quarters of non-US submarines will have advanced capabilities.[2]

Unfortunately, these operators have been able to quiet their submarines at a steady rate of about 1 db per year for the past 35 years. In fact, the US no longer enjoys the substantial acoustic advantage it once had against some of the best nuclear submarines or those operating on battery power. Whereas the detection range for low speed modern submarines used to be measured in hundreds of kilometers, today this range has shrunk to only kilometers in some cases.[3]

Air Vehicle Design

Under contract to the Navy,[4,5] KaZaK Composites is developing a sonobuoy capable of remote stand-off delivery called SPAD (Sonobuoy Precision Aerial Delivery). SPAD was designed to be interchangeable with current sonobuoys to provide this additional capability with minimal impact on support infrastructure, logistics, operations and training. This is accomplished by packaging SPAD within the "A" size format (36" long by 4.875" diameter canister) used by US and NATO forces. SPAD is stored, loaded, launched, monitored and operated in an almost identical manner to the sonobuoys currently in the Navy inventory, using the same equipment, aircraft and operator skills.

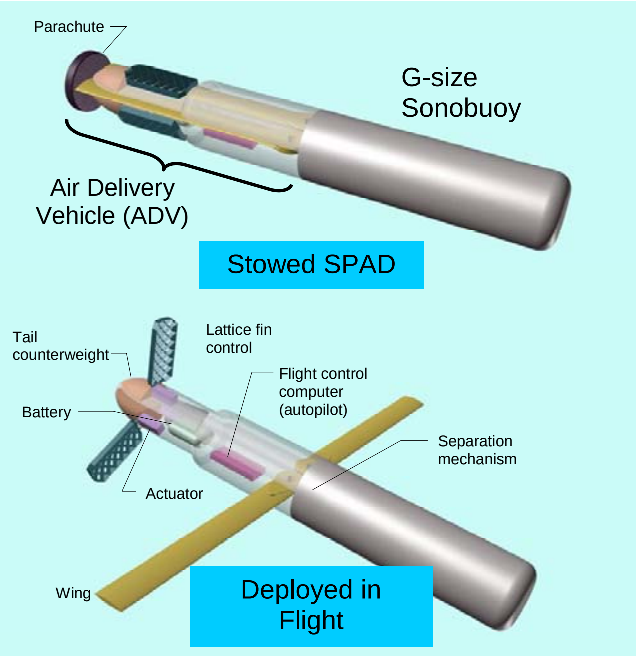

Figure 3 – SPAD design in the Stowed and Deployed condition

Advances in electronics miniaturization now allow the air-deployed acoustic sensor to be packaged into a much shorter cylinder than the 36" long "A" size format. KaZaK has partnered with Ultra Electronics' Undersea Sensor Systems Inc (USSI) who is supplying their Q53E DIFAR "G" size buoy functionally modified to operate as part of the SPAD design. The G size buoy maintains the standard A-size diameter of 4.875", but is only 16.5" long.

In SPAD, the G-size buoy is

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[2] "Technology for the United States Navy and Marine Corps, 2000-2035", National Research Council, 1997, http://www.wcdebate.com/4bconnection/0102evpol.htm

[3] Defense Technology Area Plan, Sensors, Electronics and Battlespace Environment, 1997, http://www.fas.org/spp/military/docops/defense/97_dtap/sensors/ch070303.htm

[4] Navy contract N68335-04-C-0132

[5] Navy contract N68335-05-C-0422

mated with a 19.5” Air Delivery Vehicle (ADV) to comprise the total 36” long, A-size canister, as shown in Figure 3. The ADV is essentially a deployable, unpowered UAV glider whose function is to transport the “payload” (the G-size sonobuoy) to the desired location via a preprogrammed flight path and to deploy it. Deployment of the sonobuoy is accomplished at low altitude using an internal spring to eject the sonobuoy from the ADV. At this point, the sonobuoy parachute deploys, and the buoy describes a ballistic trajectory into the water in a manner well known from conventional buoy operations.

The ADV features deployable wings and control surfaces, which fold within the canister envelope in the stored state. Upon launch from the carrier aircraft, the ADV first deploys a tail-mounted parachute to orient the vehicle with the local airstream and to obtain safe separation distance from the carrier aircraft. At that time, the parachute is released and the wings and fins are deployed, converting the vehicle into a gliding UAV.

SPAD flies a preprogrammed route consisting of intermediate waypoints, using onboard GPS for position and navigation. The final waypoint is at 200 foot altitude MSL, and a short distance from the desired Water Entry point. SPAD is programmed to attain level flight and a defined airspeed, converting descent potential energy to kinetic energy in order to obtain a well defined set of sonobuoy launch conditions. This controls the variation in the ballistic portion of the sonobuoy descent under parachute, to minimize this source of Water Entry location error. A pictorial description of the Concept of Operations (CONOPS) is depicted in Figure 4.

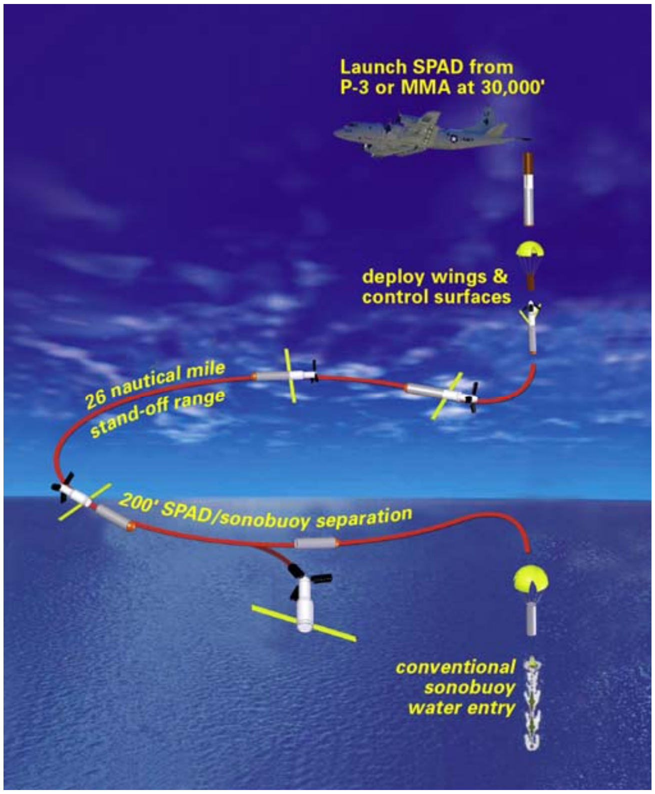


Figure 4 – SPAD Concept of Operations (CONOPS)

UAV Design Features

As an air vehicle, SPAD features a relatively conventional aerodynamic layout, with a mid wing and tail-mounted control surfaces. The wings are as long as possible to maximize aspect ratio and maximum L/D. However, the design constraint that the wings must fold into the ADV (which is less than 50% of the overall fuselage length), limits total deployable wing span. Flight vehicle characteristics are as shown in Table 1.

Table 1 – SPAD Vehicle Characteristics

Specifications			Performance		
Length	3.00	feet	Launch altitude	up to 30,000	feet
Diameter	0.41	feet	Launch airspeed	up to 370	knots
Wing Span	2.73	feet	Sea level performance		
Wing Area	0.47	sq ft	Vs1	106	knots
Aspect Ratio	15.92		V min sink	130	knots
Gross Weight	26.30	lb/sq ft	Vy max L/D	132	knots
Wing Loading	56.04	lb/sq ft	Va	222	knots
G Limits	+ 3	G	Vne	298	knots
	- 3	G	L/D max	5.5	
			V min sink	41	fps

The three tail control surfaces are of the Lattice Fin type. Originally developed in the former Soviet Union, this control surface has been used on Soviet and US missiles. They are oriented normal to the airflow, such that air passes through the openings formed by the thin walled “waffle grid” construction.

Lattice fins offer two major benefits – reduced control moment and compressed carriage. The lattice fin can be viewed as consisting of multiple short chord fin surfaces acting in parallel, versus a conventional fin of equal lift capacity, which has a single, longer chord. This translates into an order of magnitude reduction in the fin moment, allowing the use of substantially smaller and lighter control servos. In the SPAD as well as many missile designs, tail volume for servos is at a premium, and the servo size reduction simplifies packages significantly.

The other benefit afforded by the Lattice Fin is compressed carriage. The Lattice Fin is hinged and spring-loaded at the base, such that the airflow causes the fin to be self-deploying. The fins are curved to conform to the cylindrical aft fuselage of the SPAD, which also permits a more volume efficient vehicle design.

The long length of the sonobuoy payload forces what appears to be an aft placement of the vehicle wings. In order to maintain static pitch stability, a significant tail counterweight is used to maintain the vehicle center of gravity close to the quarter chord point of the deployed wings. In fact, the counterweight required, given the available coupling lengths, comprises approximately 50% of the entire ADV mass, and more than 20% of the total SPAD air vehicle mass.

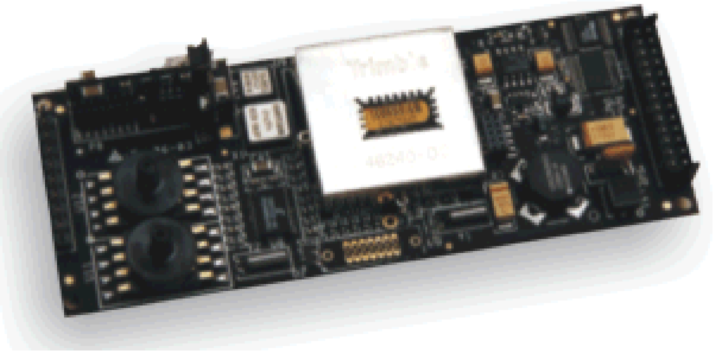


Figure 5 – MP 2028g Autopilot (3.9" x 1.6" x 29 grams)

SPAD is controlled using the MircoPilot MP 2028g single board autopilot, as shown in Figure 5. The device 3.9" x 1.6" PC board weighs less than one ounce comprising an onboard GPS receiver, 3 axis piezo gyros, 3 axis accelerometers, and onboard static (altitude) and dynamic (airspeed) air pressure sensors. The autopilot controls up to 24 servos and relays, with a 30 Hz PID control loop, 50 Hz servo update rate, and 11 bit servo resolution.

In SPAD, five outputs are controlled – the three fin servos, a SPAD parachute release device and the sonobuoy ejection device. The servos receive commands generated using PID control loops, while the other two control signals are digital On-Off commands that operate small line cutting devices to initiate the desired mechanism at the appropriate time.

Wind Tunnel Performance Testing

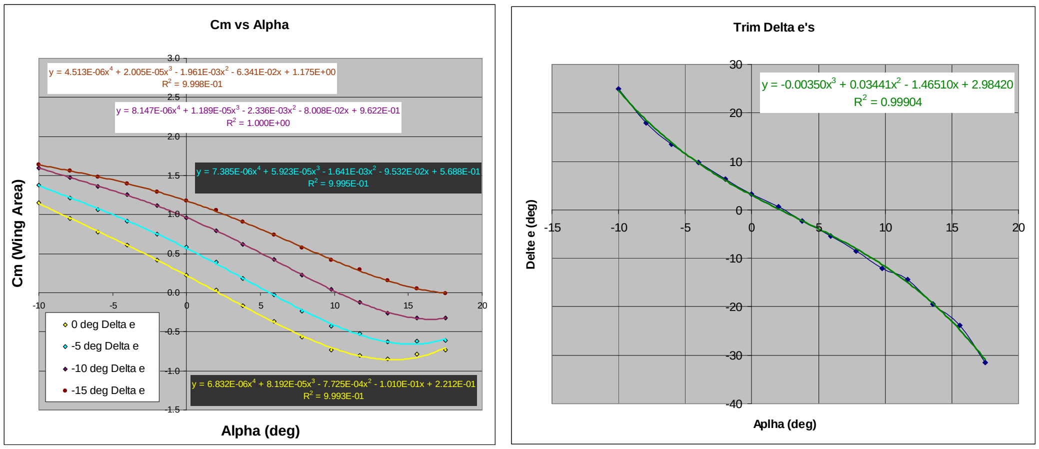
A full-scale mockup of the SPAD was tested in MIT's Wright Brothers Wind Tunnel to characterize basic aerodynamic characteristics, as shown in Figure 6. Initial tests focused on using deployed wing sweep as a means to control pitch static stability margin by moving the center of pressure, although 0° wing sweep was ultimately selected as the best balance of pitch stability and L/D performance. The final CG position was fixed from these trials, as was the mass of the tail counterweight. Several wing incidence angles were also evaluated.

Figure 6 – SPAD Wind Tunnel Model

Aerodynamic forces (lift, drag and side force) and moments (in pitch, roll and yaw) were measured for a combination of angle of attack and fin control positions. This series of tests required 41 model changes and comprised 127 test runs.

This data was used to project the position of the pitch controls for trimmed flight, as shown in Figure 7. This enabled the lift and drag performance of the trimmed vehicle to be determined, as shown in Figure 8. A drag polar for the trimmed aircraft was then derived (see Figure 9), from which glide performance was derived, as noted in Figure 10.

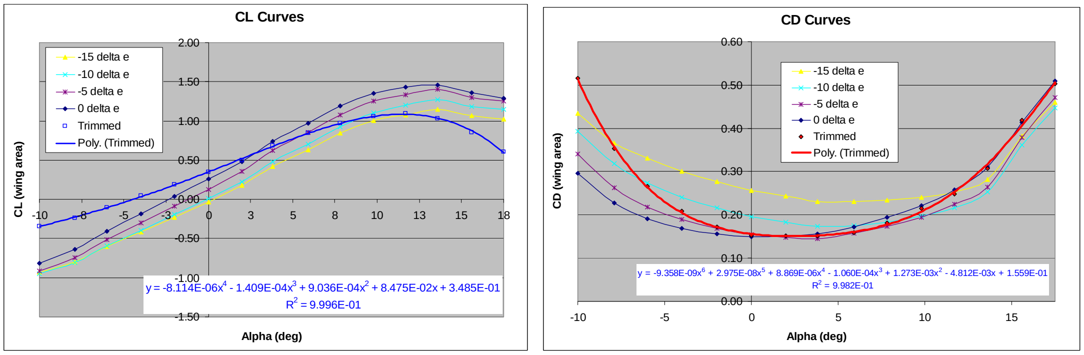
The vehicle maximum L/D is a relatively modest 5.5, which is attributable to the limited wingspan. However, this provides SPAD with an estimated glide range of 27 nm when dropped from 30,000 feet, assuming 500-foot altitude loss before wing deployment and zero wind. This range meets the SPAD design specification, and provides more than adequate range for a variety of missions.



(a) Pitching moment for various elevator positions

(b) Trimmed elevator position vs. angle of attack

Figure 7 – Wind Tunnel Data for Pitching Moment



(a) Measured and Trimmed Lift Curves

(b) Measured and Trimmed Lift Curves

Figure 8 – Wind Tunnel Data for Lift and Drag

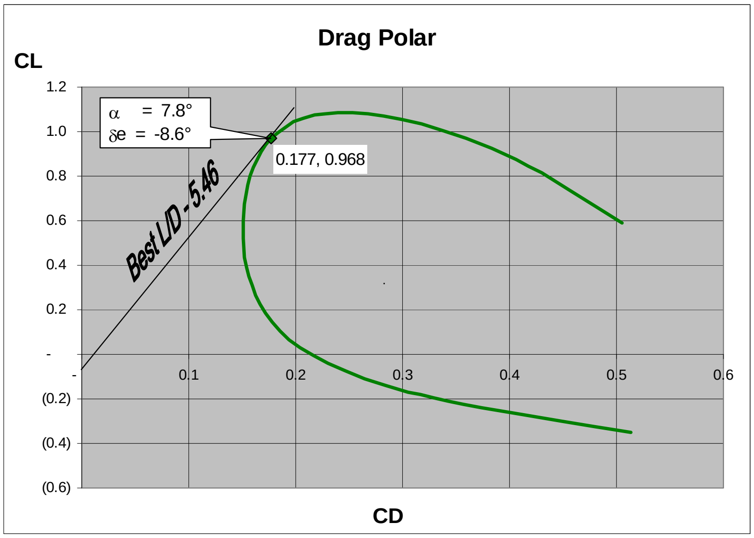


Figure 9 – Drag Polar for Trimmed SPAD Vehicle

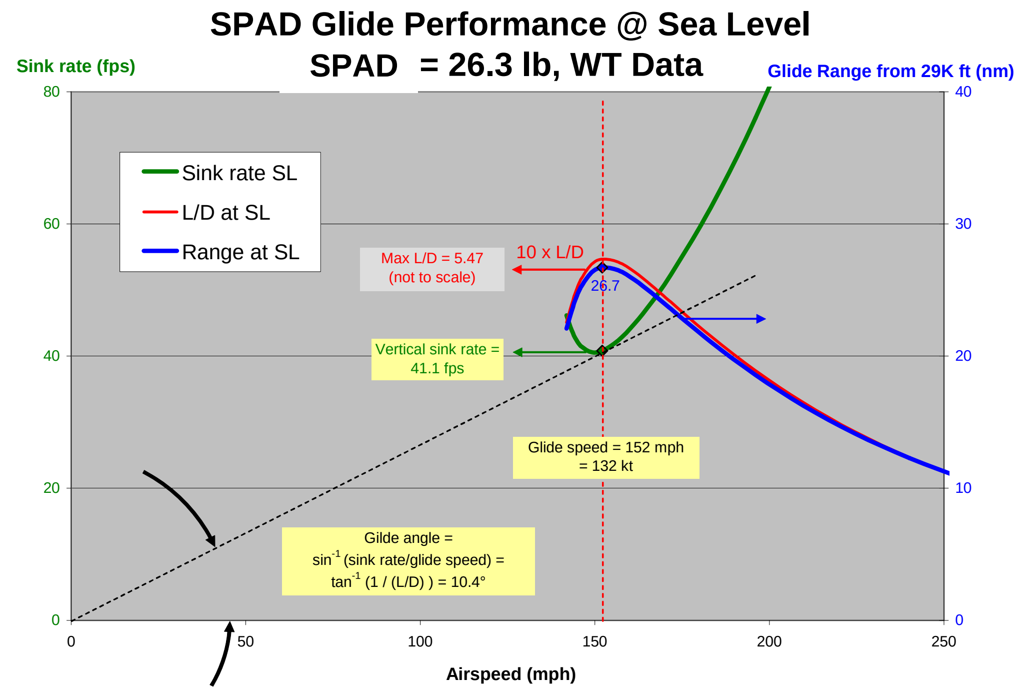


Figure 10 – SPAD Glide Performance at Sea Level

Table 2 – SPAD Mission Performance

At Sea Level		At 29,500 ft			Total mission average	
132	kt best range	215	kts		173	kts best range
5.47	L/D max	5.47	L/D max			
10.4	deg glide angle	10.4	deg			
27	nm range	27	nm		**27.1**	**nm range**
40.8	fps descent	66.2	fps		53.5	fps descent
12.0	min descent time	7.4	minutes		9.2	min descent time
2.5E+05	Re	1.8E+05	Re			
0.20	M	0.36	M			

Headwind

0.0 kt

0.0 nm decrement

27.1 nm range

Wind Tunnel Stability Tests

In addition to basic aerodynamic characteristics, stability characteristics of the SPAD were measured. This allowed calculation of autopilot PID gains for the inner flight control loops for pitch, roll and yaw controls to be performed on the ground, rather than experimentally in flight, which is often the practice for small UAV's. Knowing these characteristics, various P, I and D terms were evaluated using the autopilot dynamic simulation model HORIZON^{TM} developed by MicroPilot.

For longitudinal stability, the following characteristics were measured, some which are shown in Figures 11 and 12: $C_{m,\delta e}$, $C_{m,\alpha}$, $C_{L,\alpha}$, $C_{L,\delta e}$, $C_{d,\alpha}$, and $C_{d,\delta e}$.

For lateral stability, the following characteristics were measured: $C_{n,\beta}$, $C_{n,\delta r}$, $C_{y,\beta}$, $C_{l,\beta}$, $C_{l,\delta r}$ and $C_{l,\delta a}$

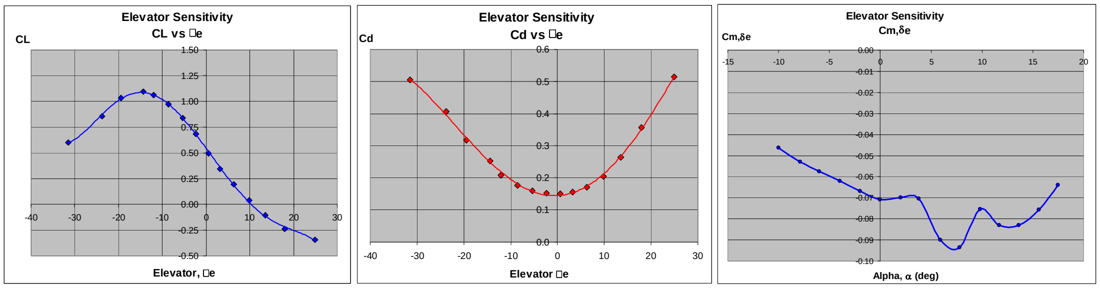


Figure 11 – Effect of Elevator deflection on Lift, Drag and Pitching Moment

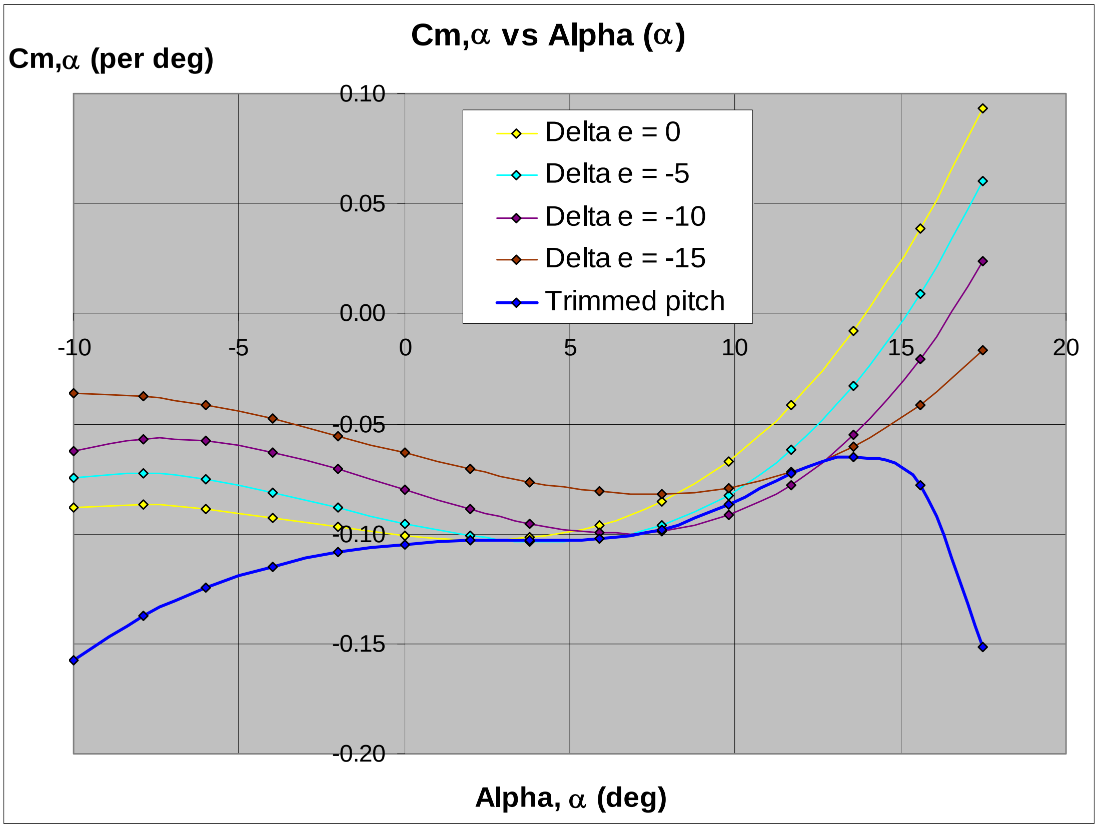


Figure 12 – Cm,α curve as a function of angle of attack

In addition, unique wind tunnel testing was performed where the SPAD was allowed to rotate about its CG while supported in the tunnel, and the autopilot actively controlling the control surfaces. Using step and doublet control inputs, the aircraft short period mode in pitch and Dutch roll mode in roll and yaw were able to be excited. This allowed fine tuning of the autopilot gains for the pitch, yaw and roll controls loops. Approximately fifty gain tuning runs were performed in the wind tunnel in a much more rapid, cost-effective and safe manner than had these trials been performed experimentally in flight.

Flight Test Plans

SPAD will be flight tested in the third quarter of 2007. The plan calls for initial trials to release the vehicle vertically in free fall from 10,000 feet. The vehicle will accelerate to exceed the stall speed, when the wings and fins will deploy. At this point, the vehicle will pitch up to attain various glide speeds to measure actual glide performance. A special version of the vehicle, called SPAD-RV (for Recoverable Version) will be used, where the volume normally used for the sonobuoy payload will be used instead for a large recovery parachute. Early flight tests will be conducted over land at the Whiter Sands Missile Range, which has open terrain for easy recovery.

Ultimately, it is our intent to conduct over water test flights, with test drops up to 30,000 feet.

Acknowledgements

The authors wish to acknowledge the contributions of Harry Shook, Pat McCammon and Bill King of Ultra Electronics, Undersea Sensor Systems Inc (USSI) for their advice and assistance on matters pertaining to sonobuoy design and operation, and for supplying the sonobuoy prototypes used on SPAD. Mark Miller of Dynetics performed the CFD modeling of the SPAD and contributed to the aerodynamic design and wind tunnel test planning. Howard Lowen of MicroPilot has also assisted KaZaK in the customization of their software for use on the SPAD.