

Autonomous Aerial Payload Delivery System “Blizzard”

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This paper presents a self-contained aerial payload/sensor delivery system Blizzard and discusses its potential applications.

Abbreviations

AADS	=	autonomous aerial delivery system
ADS	=	aerial delivery system
CEP	=	circular error probable
C ²	=	command and control
IED	=	improvised explosive device
GNC	=	guidance, navigation and control
GPS	=	Global Positioning System
GSM	=	Global System for Mobile (Communications)
MCCC	=	mission C ² center
PATCAD	=	Precision Airdrop Technology Conference and Demonstration
SA	=	situational awareness
SUV	=	sport utility vehicle
UAV	=	unmanned aerial vehicle
YPG	=	U.S. Army Yuma Proving Ground

I. Introduction

IMPROVED accuracy of payload delivery with the help of autonomously-guided ram-air parafoils, especially for the ultra-light-weight systems, opens a door to a variety of new applications. Among them is the deployment of multiple guided systems from unmanned aerial vehicles, hence providing a robust tool for fast and safe delivery of small items, supplies, ground robots or sensors.

In 2008, with the support of the U.S. SOCOM, the Aerodynamic Decelerator Systems Center (www.nps.edu/ADSC), presented a miniature prototype of an autonomous Aerial Delivery System (ADS) Snowflake, developed by the team of researches from the Naval Postgraduate School and University of Alabama.¹ Since then, almost two hundred drops have been performed in California (Marina Municipal Airport and Camp Roberts) and Arizona (Yuma Proving Ground and Kingman). During the very first series of drops in May of 2008 Snowflake ADS exhibited 55m circular error probable (CEP), well exceeding the standard requirement of 100m set

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for the large systems (despite the fact that light-weight systems compared to the heavy-weight systems are more susceptible to the unknown variable winds). Unlike other systems, Snowflake ADS utilizes the inertial trajectory which allows accounting for expected winds, planning and accurately tracking the final standard-approach-pattern maneuver and landing safely into the winds.^{2,3} Due to several improvements to Snowflake's guidance and control algorithm introduced during several sets of tests in 2009, the touchdown accuracy of Snowflake was eventually brought down to 10m CEP. Other novelties included networking and global reach capability.⁴

Integrated with one of the best Tier II class unmanned aerial systems, Arcturus T-20, equipped with the autopilot and optical sensors to find and track targets and capable of carrying up to 65lbs of payload, Snowflake ADS comprises a complete, self-contained mobile combat system for precise aerial delivery with a global reach capability. This system, Autonomous ADS "Blizzard" (AADS) was first demonstrated in public at the Precision Airdrop Technology Conference and Demonstration (PATCAD) at the U.S. Army Yuma Proving Ground in October of 2009. Since then, the system has been presented at several trade shows and is currently used as a tool to continue developing and testing novel concepts in precise aerial delivery. To be more specific, week-long tests take place every three months at Camp Roberts, CA within the U.S. SOCOM-NPS Field Experimentation Cooperative.

The paper presents an overview of the system, its basic performance and technologies currently under development that rely on the "Blizzard".

II. Overall Description and Concept of Operations

The four major components of the Blizzard AADS are: i) the T-20 unmanned aerial vehicle (UAV); ii) ADS Snowflake itself; iii) ground mission command and control center (MCCC) for handling mission planning, launch / recovery operations and passing any necessary information to / from the Blizzard ADS to the operator, and iv) (optional) ground target weather station.

A T-20 UAV is the largest vehicle produced by Arcturus-UAV (Fig.1). With a 17' wingspan, this Tier II class vehicle offers the ability to carry up to 65lbs of payload in excess of 16 hours. It is powered by a versatile 10 horsepower 4 stroke engine offering smooth, quiet and efficient power. With most of the fuel carried in the wings, T20 has a massive payload bay measuring 11½"×11½"×34" clear, with more available. Avionics are carried in the aft portion of the fuselage.

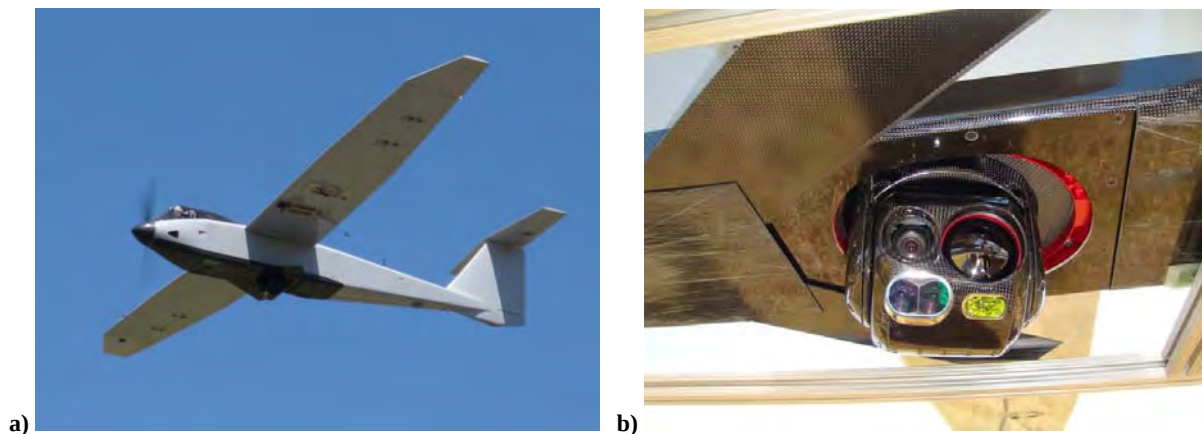


Figure 1. Arcturus T-20 UAV (a) equipped with TASE300 gimbaled camera (b).

The T-20 features molded modular construction for ease of parts replacement. The live skin hinging system ensures control surface integrity and low maintenance. The T-20 is pneumatically launched and belly landed. This allows the vehicle to operate from austere unimproved locations. No runway is needed to fly. A replaceable belly skid absorbs the abrasion and is changed in minutes (after 20-30 landings). Hence, any reasonably level open space is the only requirement for full operational capability.

The Blizzard AADS utilizes a retracting TASE300 (or TASE200) high performance gimbal (seen in Fig.1 and shown in more details in Fig.2) featuring a full 360° un-obstructed field of view, direct drive brushless motors for increased stabilization performance, integrated global positioning system (GPS) receiver plus three-axis inertial measurement unit for standalone operation that eliminates the need for vehicle mounting calibration, and integrated image processing board. It includes the 640 pixels by 480 pixels long-wavelength infrared camera and an FCB-EX980 Sony block camera with optional laser pointer, range finder and illuminator (as shown in Fig.2). Operation modes include pilot mode, stabilized mode, Lat/Lon/Altitude mode, object tracking, and geo-location estimation. Blizzard's gimbal provides a continuous pan and tilt of +40° / -220° with a 200°/sec slew rate and 0.023° pointing

resolution (0.05° for TASE200), i.e. 1m per each 2.5km of slant distance (2m for TASE 200), and is capable to operate day and night.

The Cobham Tactical Communications and Surveillance miniature microwave standard definition video transmitter coupled with a 2Watt variable efficiency power multiplier (Fig.3) allows transmitting the encrypted mpeg4 video stream taken by the camera down to MCCC for up to 50 miles with 5Db margin. The T-20 UAV utilizes a simple 4Db blade antenna under the tail and MCCC includes a two-patch antenna with a total coverage of 90 degrees. As is well-known for UAV applications, signal bounce off the earth or buildings may induce fading, causing signal breakup. The Cobham receiver uses spatial diversity to overcome fades and multipath and enhance video quality. To be more specific, it uses a robust digital modulation system known as coded orthogonal frequency division multiplexing, relying on a voting logic board which votes for the best signal during the horizontal antenna beam electronic scan 15,000 times per second. The system works with the smallest angle of line-of-sight clearance above the ground, and for short-range operations (less than 15 miles) allows non-line-of-sight operations inside canyons, around the hills and tall buildings (urban operations). Therefore, there are almost no restrictions on accurate and persistent target tracking. Figure 3b show an example of the data, where the coordinates of the located wounded soldier who is in need of medical supply are computed by the TASE300 sensor and then passed wirelessly to the Snowflake ADS, which in turn computes the release point and passes it back to UAV's autopilot to execute.

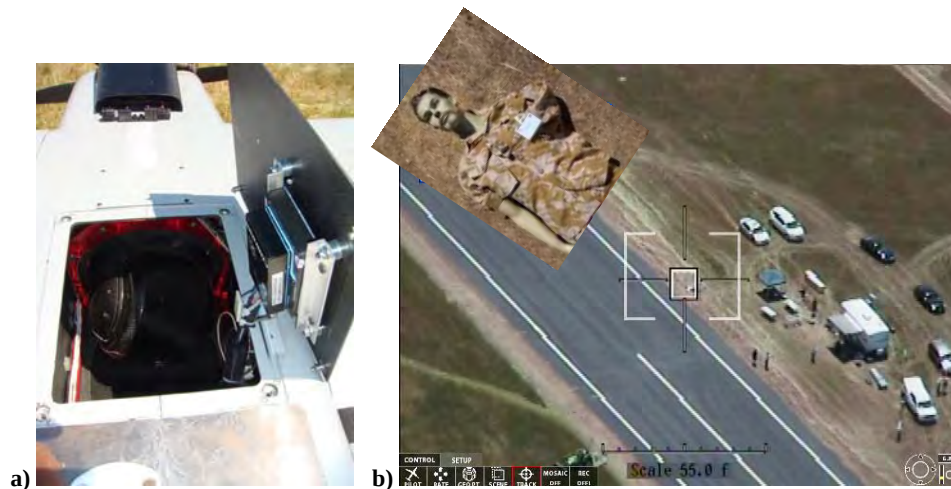


Figure 2. Cobham microwave video transmitter (a) and desired impact point chosen using TASE300 sensor (b).

The Blizzard modification of the Snowflake ADS consists of a carbon-fiber composite payload container (Fig.3a) hosting a guidance, navigation and control (GNC) unit along with the servos and packed parafoil (Fig.3b). Blizzard features two containers, one under each wing, that are capable of carrying up to 30lbs each (utilizing three different-size canopies). The size of the GNC unit can be reduced by a factor of 10 allowing more space within the pod, but for research purposes it is kept the same size as the original Snowflake ADS as discussed in Section III. The complete, ready-to-be-launched Blizzard system is shown in Fig.4a.

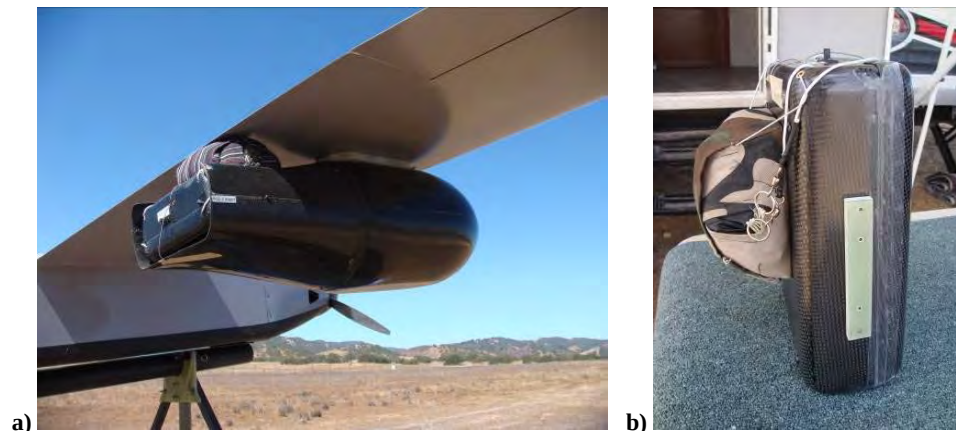


Figure 3. Blizzard Payload container (a) with a modular GNC unit (b).

The ground component is presented by the MCCC residing in a recreation vehicle as shown in Fig.4b (also see it in Fig.2b). A mission operator (Fig.5a) supervises all operations and is able to exert control and change any mission parameter as needed.

Snowflake ADS target assignment can be accomplished in several ways. First, the coordinates of the target(s) can be entered into the system during the pre-flight checks or in flight via the MCCC or from anywhere in the world via the Internet (this capability will be discussed in Section IV). Another scenario is that the coordinates of the target are computed automatically by choosing any point within the image as shown in Fig.3b. Finally, the target coordinates can be transmitted from the ground with the help of the target ground weather station (Fig.5b). This optional Blizzard component not only allows transmitting the coordinates of the delivery point itself, but also provides a very cheap and yet effective way of increasing accuracy of payload delivery by measuring and transmitting the ground winds. This palm-size device needs to be mounted at the desired target location, and may be deployed either with a vane, if a soft landing is needed, regardless the delivery direction, or without it, as shown in Fig.5b, if a certain delivery direction is preferable (in the mountains). Day or night the requested payload will be delivered right to the target.

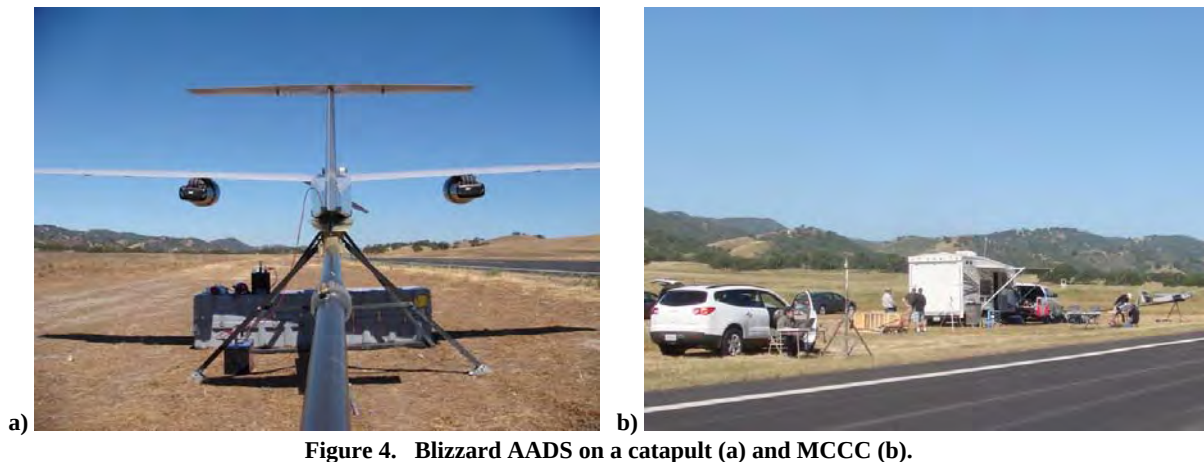


Figure 4. Blizzard AADS on a catapult (a) and MCCC (b).



Figure 5. Blizzard operator (a) and an optional miniature target ground weather station (b).

III. Overview of the Snowflake ADS

The original Snowflake ADS consists of a 4"×8"×10" payload container with the GNC unit inside it. (Fig.6a features the original design as opposed to the Blizzard design of Fig.3b, but the GNC unit is exactly the same for both designs.). The GNC unit consists of avionics and control actuators. As opposed to other ADSs, the Snowflake avionics include not only a GPS receiver, but also three accelerometers, gyroscopes and magnetometers, and a barometric altimeter, all integrated on a single circuit board.¹ The dry weight of the Pelican-case system is less than 4.3lbs.

In its original design with a smallest 4.5" by 2.1" two-skin canopy the Snowflake ADS is capable of carrying additional 1...3lbs of payload (whatever fits inside the Pelican Container) and features the descent rate of 12ft/s,

forward speed of 14kts, glide ratio of 2, and minimum turning radius of about 50ft. (Two other Blizzard canopies, 25 and 36 sq.ft, are the scaled-up copies of the smallest one.)

Once installed under the wing using a pair of reciprocal shoes, Snowflake ADS is equipped with an arming lanyard attached to the UAV (Fig.6b). Once reaching the computed release point the Blizzard pod is released and a lanyard is pulled out of Snowflake (Fig.7) triggering a consequent canopy release.

Upon release from an UAV Snowflake ADS steers autonomously towards a predefined stationary or moving target (Fig.8) constantly updating and tracking the inertial trajectory (Fig.9).^{2,3} It first steers towards the loiter area (Phase 1) where it estimates winds (Phase 2), then exits the upwind pattern (Phase 3) and glides downwind (Phase 4) to perform a base turn (Phase 5) and final approach (Phase 6). This final turn relies on the optimal inertial trajectory updated every second or so, depending on tracking performance. The precision placement algorithm to control the system during all phases is based on model predictive control.² As mentioned in Section II, Snowflake's GNC allows landing with any predetermined heading including soft landing into the wind. To date, Snowflake ADS has been deployed almost 200 times from the altitudes of 2,000' up to 12,000' above the target elevation and its typical performance is 10m CEP with the remaining 50% landing within 30m from the target. Without a ground weather station the accuracy degrades to 20m CEP, but a 30m threshold for the remaining 50% remains the same.

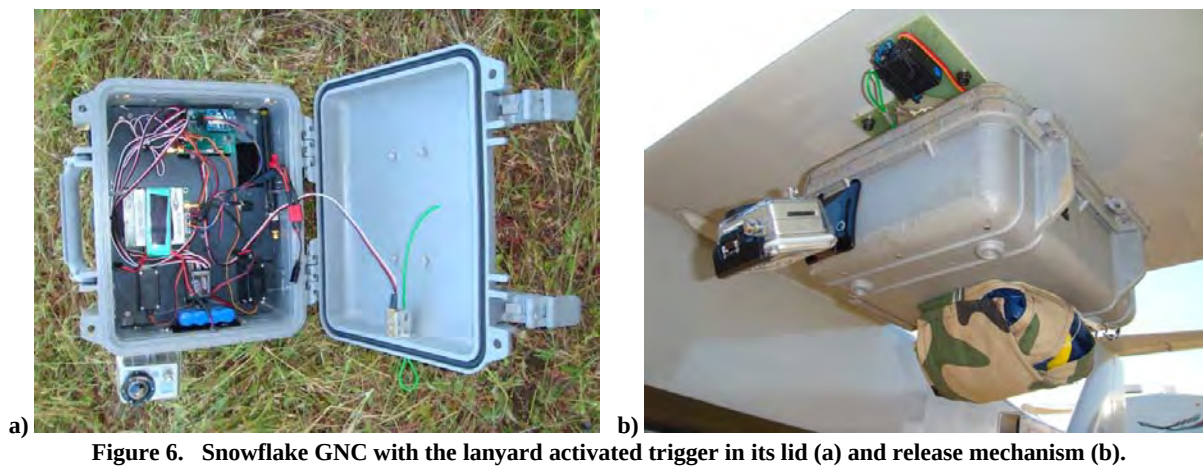


Figure 6. Snowflake GNC with the lanyard activated trigger in its lid (a) and release mechanism (b).

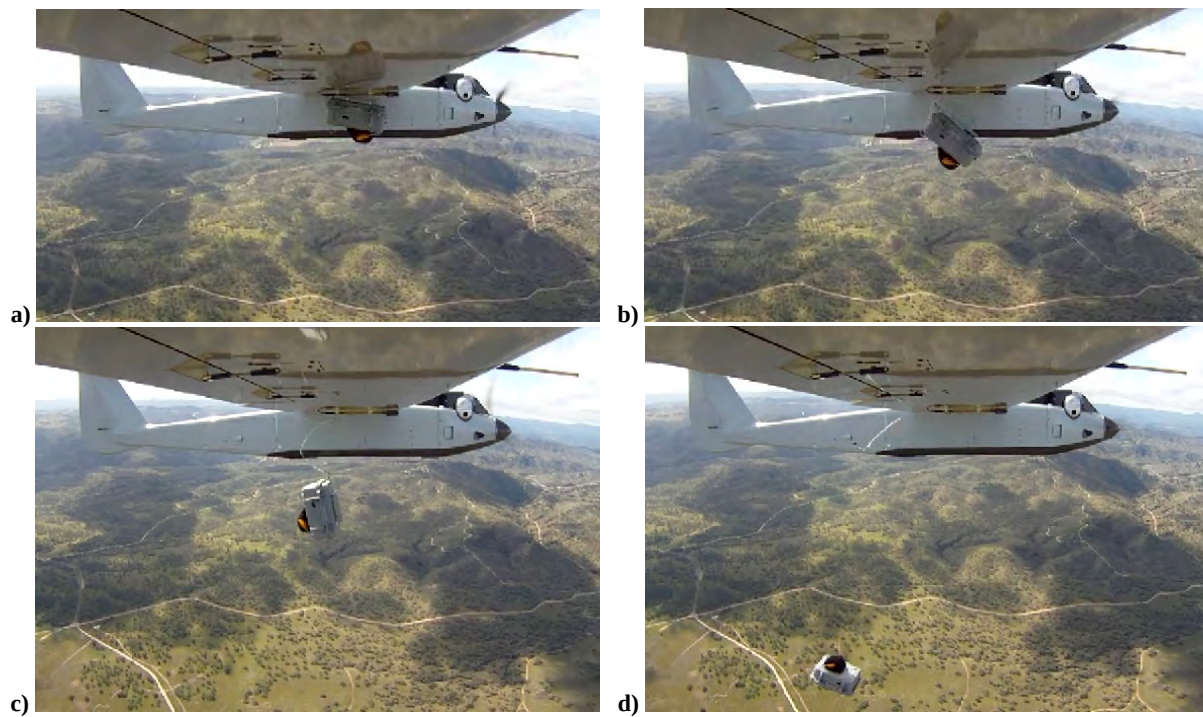


Figure 7. Snowflake ADS release sequence.

It should be pointed out that the crucial phase of autonomous descent is a loitering pattern (bounded by four points in Fig.9). It is this phase where Snowflake estimates its own performance and current winds. The GNC algorithm is designed so that it can be easily put on any other system with very little modifications, because the parameters of the system (descent rate, forward speed, turn radius) are not hard-coded but rather are being estimated in flight. In this case the user can change the canopy or weight of the system not worrying about the consequences. Hence, it is important that the computed release point is computed so that it allows accommodating at least one full circle in the loitering pattern (with two loops being the optimal). If the aforementioned parameters are hardcoded (meaning that the system will be dropped in exactly the same configuration (canopy size, weigh) all the time, then this requirement can be removed.

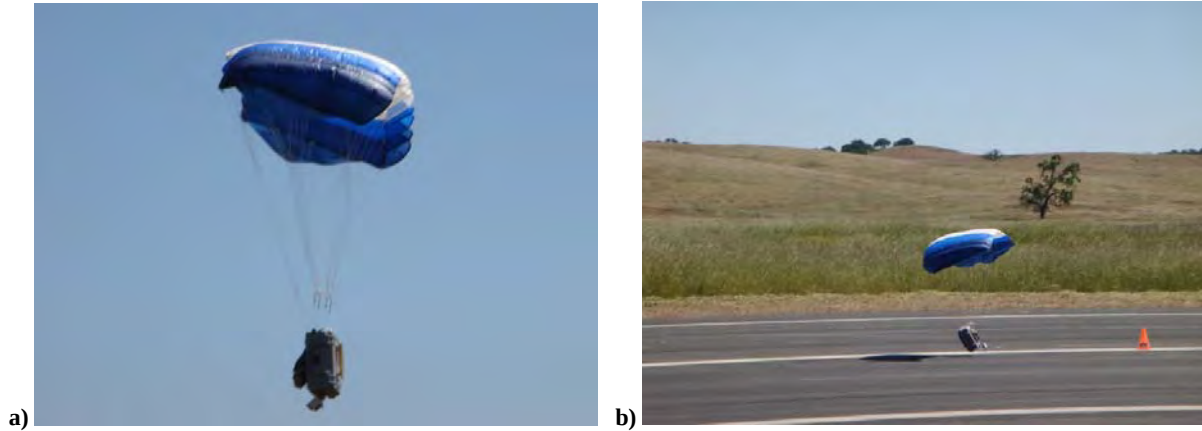


Figure 8. Fully deployed Snowflake (a) and soft into-the-wind touchdown right on target (b).

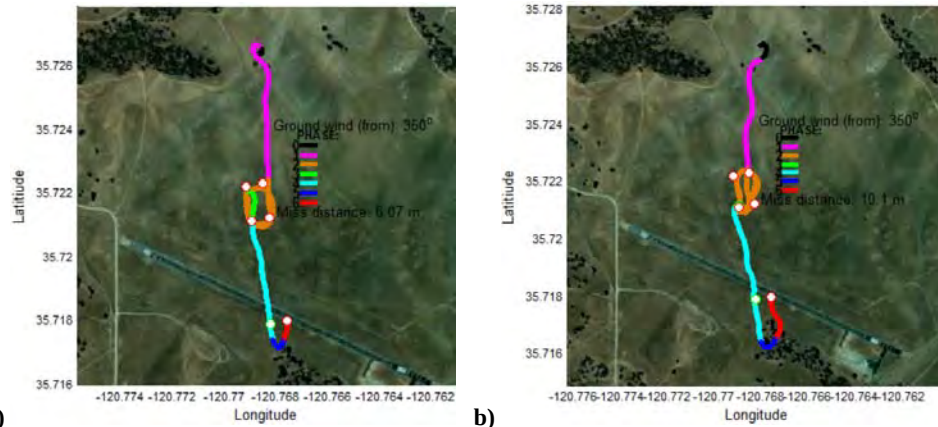


Figure 9. Bird-eye view of a typical Snowflake's trajectory featuring 6m (a) and 10m (b) accuracy.

For some applications (see more in Section VI) even 10m accuracy may not be enough. For example, a wounded soldier needs emergency medical supplies to be delivered within arm's length (Fig.10a). That is when the Blizzard pod may host the fifth critical element, a ground robot (Fig.10b). Upon touchdown such a robot crawls out of the pod and moves closer to the target, carrying necessary supplies or sensors.

IV. Network Architecture

To mitigate the effect of unknown and constantly changing ground winds, the terminal guidance algorithm employ continuous real-time reoptimization of the final turn.^{2,3} This is one of the unique features that distinguishes Snowflake's GNC from that of all other known systems. Another technique to achieve a high touchdown accuracy is networking, enabling communication between multiple descending ADSs, UAV, ground weather stations and an operator, who can reside anywhere in the world.⁴

Depending on application the simplest way of communicating is using the commercial network or its tactical extension.⁴ Figure 11a shows the network architecture in this case. Ground target weather stations (Fig.5b), based on a portable Kestrel 4000 weather device, measure the ground winds and constantly uplink them to the descending Snowflakes via a Blackberry cell phone interfacing with the Kestrel via Bluetooth module. In this case the

Snowflake ADS payload also includes a Blackberry cell phone, accepting the ground weather station updates and passing them on to an autopilot using Bluetooth interface as well.

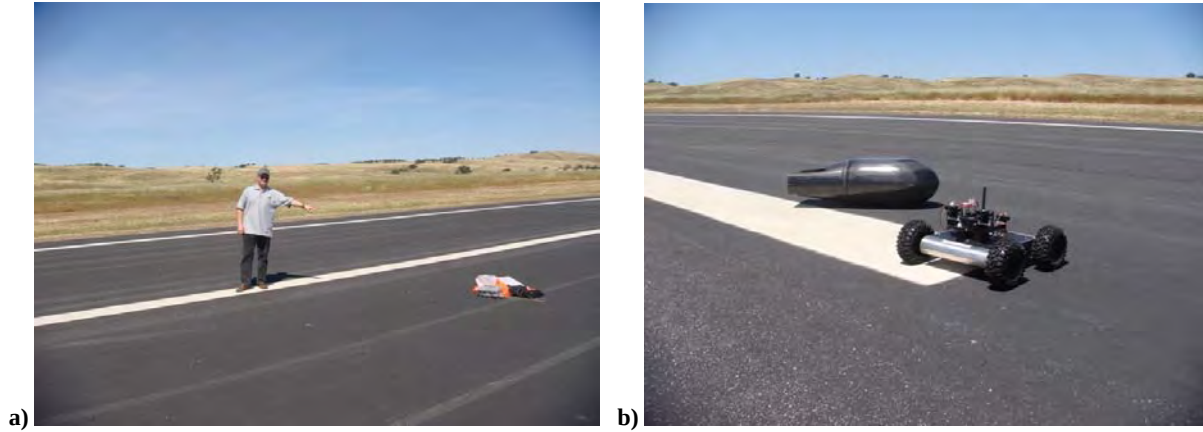


Figure 10. Another precise delivery (a) and the usage of the ground robots (b).

Another control and command (C^2) architecture (Fig.11b) does not rely on Global System for Mobile Communications (GSM) at all. In this case, a primary mode for a weather station to communicate with a descending Snowflake is via the miniature computer and 900MHz FreeWave radio module residing in a small box nearby (shown in the front plane of Fig.4b and also addressed in Section V). The weather station talks to this computer wirelessly, using a Bluetooth interface.

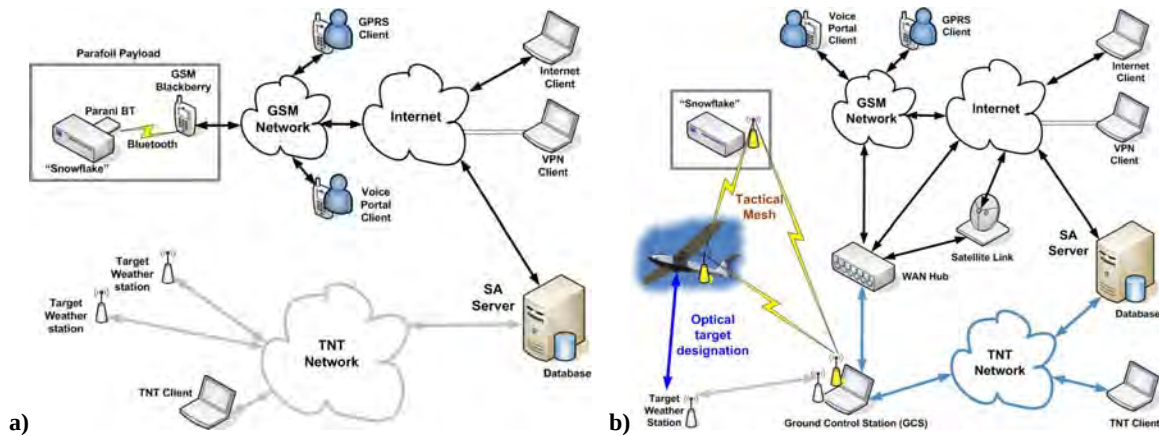


Figure 11. GSM-based (a) and RF-based (b) network architectures.

Originally developed for the single purpose of communicating with the target weather stations to enable better touchdown accuracy of the Snowflake ADS, the developed architecture allows doing much more. Specifically, either of the two architectures of Fig.11 provides the most current data to a situational awareness (SA) display, and enables communication with the descending system from anywhere in the world via computer (Internet), GSM handheld, or voice portal to dynamically reassign target or change any other mission parameter.

In the case of a smaller payload (sensors, meshcards / network nodes) the inner payload bay of Arcturus T-20 UAV can host up to a dozen smaller Snowflakes. The under-the-wing containers of Fig.3a can be used for the same purpose. In this case multiple descending systems can be used to establish a short-term moving network-in-the-sky (see more details in Section VI). Among others, this network can also be used to share winds and SA data between multiple systems for a variety of collaborative control missions. They will also be able to talk to other assets residing in the air or on the ground.

V. PATCAD'09 Performance

In 2009 the Blizzard system was demonstrated at the major showcase, the 5th PATCAD in Yuma, AZ. This demonstration featured about a dozen different-weight systems. For the sake of comparison Figs.12,13 show the overall results of several low-weight systems including Snowflake.⁵ It should be noted that 2009 demonstration featured very strong ground winds often exceeding 30kts, hence the performance of all system was definitely

affected by this. The smaller the weight of the system and therefore the slower the forward speed is, the more effect these high winds have.

Consider Fig.12a presenting the results for System 4 (Systems 1-3 were the heavier systems and are not considered here). These results are somewhat typical for the systems relying on empirical guidance algorithms. Sometimes the algorithm works, sometime unknown surface winds blow the system away from the target. The performance of two other systems (5 and 6) is presented in Figs.12b and 13a. To be fair, some of the drops that resulted in the very large touchdown errors, either because of a mechanical or algorithmic failure are excluded from the data. For example, for the best 11 drops of System 5 shown in Fig.12b (5 drops with an error exceeding 160m were excluded because they were far away from the main group of results) the achieved accuracy was 44m. As seen, the claim that the lighter systems inherently exhibit a better performance,⁶ does not hold. The same observation can be made for System 6 (Fig.13a). Even if we consider 58% of the drops, the CEP value is still too high and exceeds the limit of 100m established for the larger systems. Obviously, for lighter systems the same winds cause the larger touchdown errors and dispersion.

Figure 13b presents the overall Snowflake's results at PATCAD. For one of the released five systems the control lines were twisted over the canopy so it was not controllable and therefore is excluded from consideration. For the remaining four systems, the achieved CEP was below 40m, which may be considered as a bad result (cf. with Fig.9). A closer look at the Snowflake trajectories explains what happened. To this end, Fig.14 shows two of four PATCAD trajectories. Notably, they look identical with the ones presented in Fig.9. However, because of the uniqueness of the Blizzard AADS (experimental versus commercial), the YPG Range Control set the release altitude much lower compared to all other systems and because of the strong winds, exceeding Snowflakes forward speed of 14kts, moved the release point further upwind. As a result, not a single drop had a full loop in the loitering area, i.e. system performance and winds estimates were very poor. Taking these factors into consideration brings a new light to Snowflake's data presented in Fig13b.

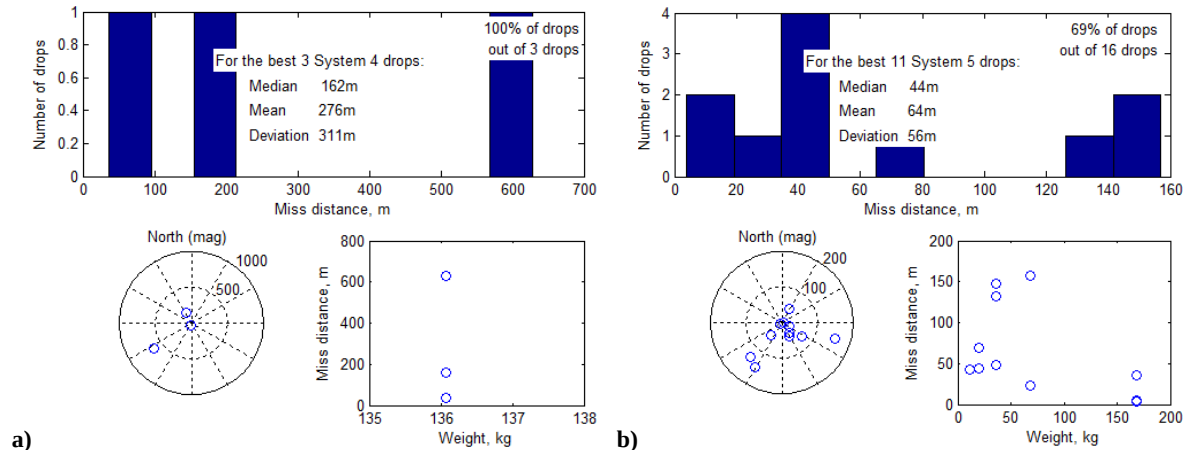


Figure 12. PATCAD'09 performance of a sub-centner-category System 4 (a) and 5 (b).

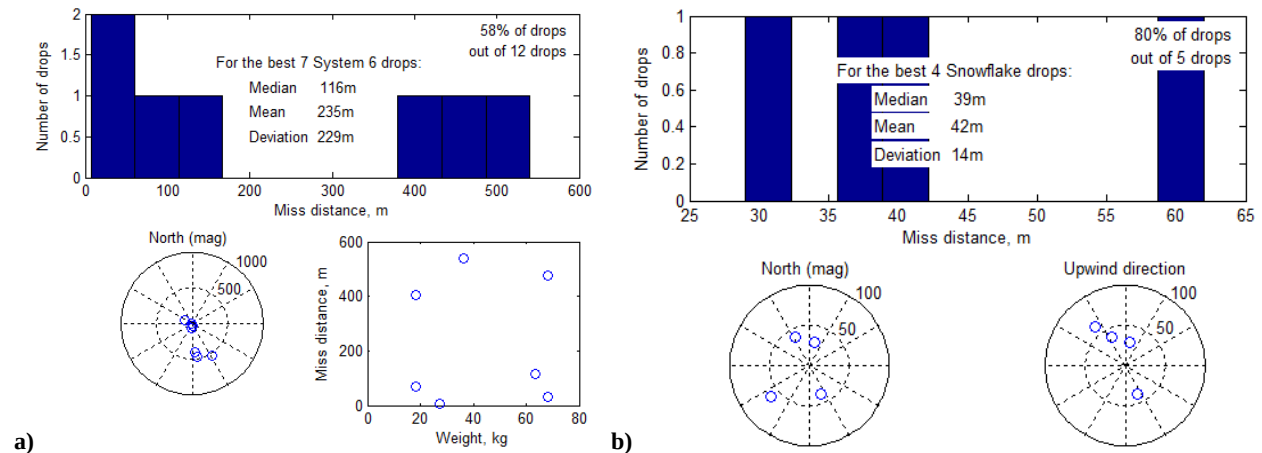


Figure 13. PATCAD'09 performance of ultra-light System 6 (a) and Snowflake (b).

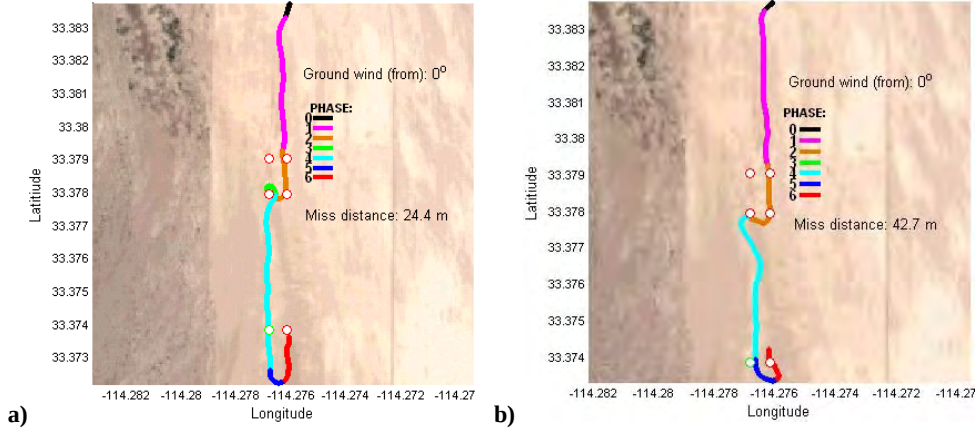


Figure 14. Two out of four Snowflake performance at PATCAD'09.

Compared to GNS algorithms of Systems 4-6, Snowflake's GNC algorithms happened to be more robust. Every time the Snowflake ADS was deployed it featured almost the same inertial trajectory taking even strong winds into account and using them rather than fighting against. Table 1 presents the comparison table of all the results discussed earlier in this section.

Table 1. Comparison of light ADSs' PATCAD'09 performance for the best drops

System	Total # of drops	% of excluded drops	CEP, m	Average error, m	σ , m
System 4	3	33	100	100	88
System 5	16	40	44	64	56
System 6	12	67	50	56	48
Snowflake	5	20	39	42	14

VI. Current and Future Development

While the Blizzard system represents a complete almost fielded system, ready to be used in different capacities, it also represents a great tool to do some basic research and prove new concepts. To this end, Fig.15 shows a variety of projects the NPS-UAH-Arcturus-UAV team is working on.

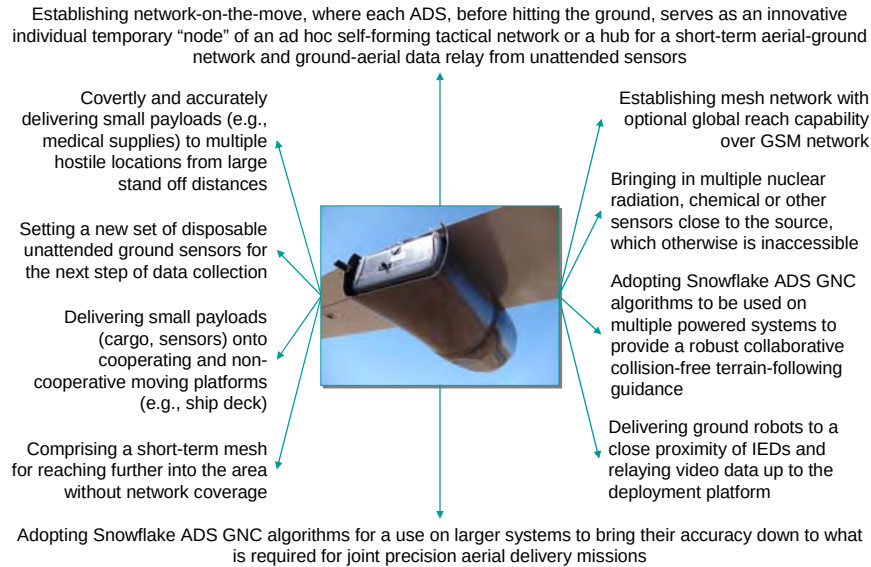


Figure 15. Blizzard AADS applications.

Let us briefly elaborate on a couple of them. As mentioned in Section III, the Blizzard delivery pod can carry an autonomous ground robot like the one shown in Fig.16a. Snowflake ADS can also be scaled up to carry a larger robot with more capabilities, for example to pin-point delivery of medical supplies/sensors, providing the video link,

or disarming an improvised explosive device (IED). Figure 16b features the ground robot in operation, driving towards the target weather station (compare it with that of Fig.5b for the original GSM-based network architecture).

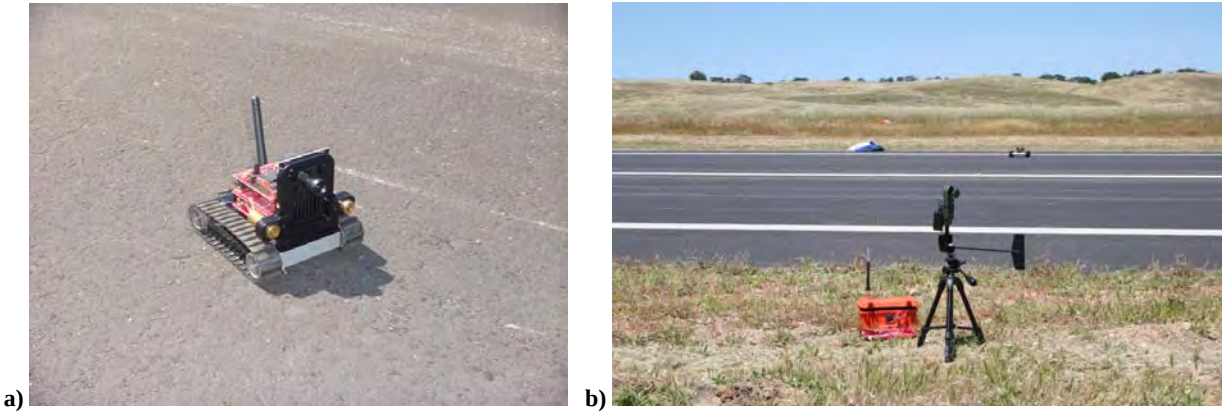


Figure 16. Ground robot to be deployed by Blizzard system (a) to go to the target upon deployment (b).

Another natural extension of the Snowflake's GNC algorithms is to accommodate landing onto a moving target, such as the flight deck of a ship. To date, two drops have been performed with a standard sport utility vehicle (SUV) being a moving target and broadcasting its GPS position to a descending ADS. Snowflake then estimates the motion parameters of the moving target and constantly replans its trajectory. To this end Fig.15a shows the touchdown moment for the second drop. While the miss distance for the first drop was about 10m, for the second drop Snowflake almost hit the moving car. For the safety reason further experiments will utilize a specially designed moving platform shown in Fig.15b. This application may involve passive platform motion estimation / navigation, hence the Snowflake GNC is currently adopted to incorporate the video input. In the meantime all image processing is done offline. The video footage is currently gathered with GoPro cameras attached to the bottom of Snowflake as shown in Figs.6b and 8. Figure 17a shows a couple of potential targets in the field of view to find and track and Fig.17b shows a couple of images of the moving target (SUV) taken by descending Snowflake as shown in Fig.15a.

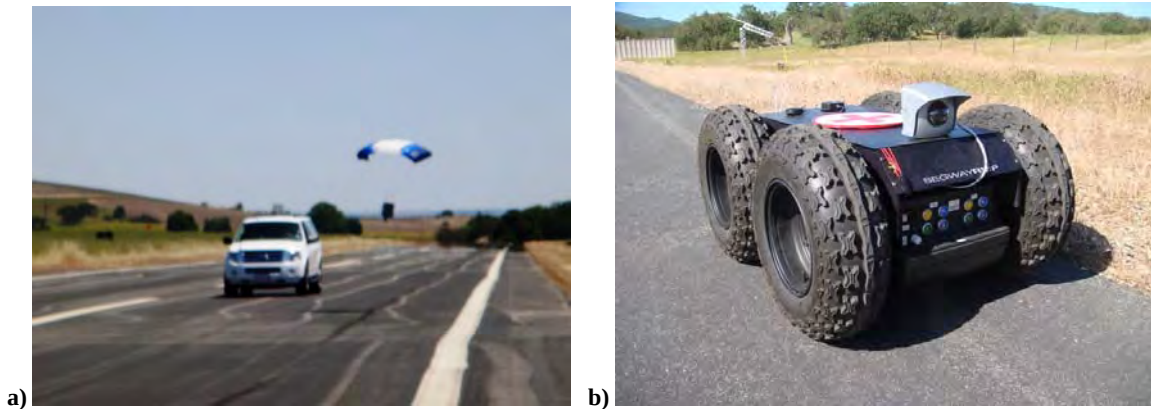


Figure 17. Landing onto a moving SUV (a) and future moving heavy-duty target platform (b).

One more area of current research is exploring a capability to use multiple Snowflakes to form, maintain and reconfigure a tactical network. To conclude, Fig.18a features a UAV/Snowflake tracking capability developed in relation to the Blizzard system and Fig.18b shows the entire Blizzard team with the major components of the system they developed and do research with.

VII. Acknowledgements

The authors would like to thank Dr. Buettner, the Director of the U.S. SOCOM-NPS Field Experimentation Cooperative for his continuous support of the Blizzard project and to the personnel of the U.S. Army Yuma Proving Ground for helping with the testing of the original Snowflake ADS. The wind data collected during these drops were and still are a valuable source for understanding how to properly model surface winds for Snowflake applications.

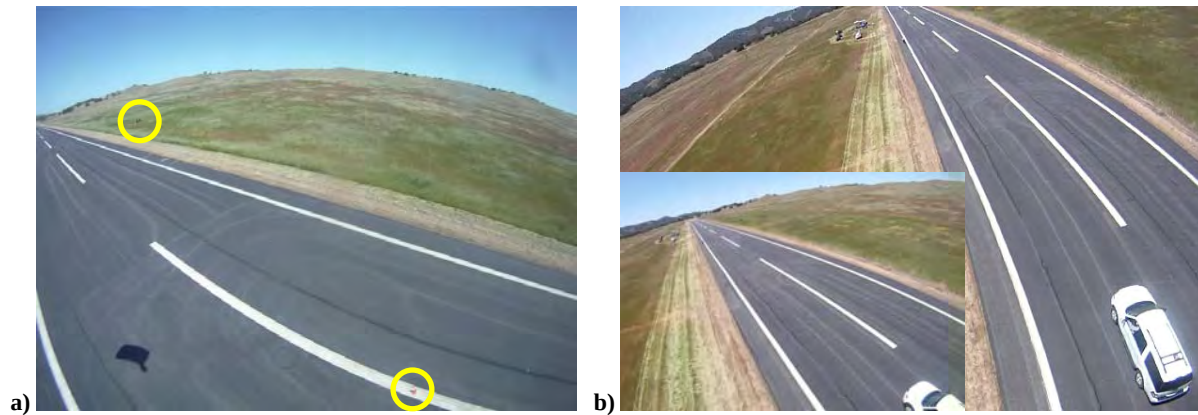


Figure 16. Two potential targets to track (a) and moving target snapshots (b).

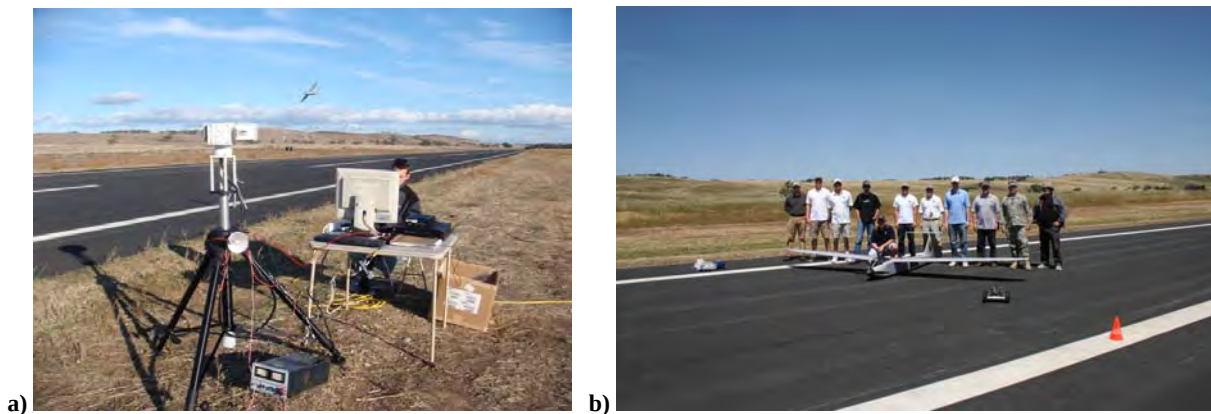


Figure 17. Snowflake ADS / T-20 UAV tracking station (a) and a Blizzard team with the Camp Roberts Base Commander (b).

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