Instrumentation of Paratroopers and Large Parachute Pallet Loads

Joseph M. Strus, Earl G. Blackwell, Christian A. Gellrich, Michael R. Kirkpatrick, James W. Sinko, SRI International

BIOGRAPHIES

Joseph M. Strus is a Systems Analyst at SRI International where he has worked on precision navigation applications since 2001. Previously, he was a GPS Systems Engineer with the Government Systems Division of Rockwell Collins. Dr. Strus received his B.S. (1986) and Ph.D. (1994) in Mathematics from the University of Illinois at Urbana-Champaign.

Earl Blackwell graduated from the University of Tennessee in 1957 with a B.S. in Engineering Physics. He continued graduate work at UCLA and USC and joined SRI International in 1970 where he is now a Senior Technical Advisor and SRI Fellow. He has specialized in GPS technology since 1978.

Christian A. Gellrich is a Senior Research Engineer at SRI. He received a B.S.E.E. from Worcester Polytechnic Institute in 1986 and an M.S.E.E. from the University of Rhode Island in 1989. He specializes in digital signal processing and data acquisition system design.

Michael Kirkpatrick is currently a Development Engineer at SRI International, where he has been involved in hardware and software systems design and development since 1985.

James W. Sinko is a Principal Engineer at SRI International. He received his B.S. (Engineering Science) and M.S.E.E. from Stanford University, and his Ph.D. (EE) from the University of Rochester. Dr. Sinko has been with SRI since 1967, working with radar and aircraft systems. For the last 9 years, he has been working with precision GPS for military and civil applications.

ABSTRACT

The US Army Operational Test Command, Airborne & Special Operations Test Directorate (ABNSOTD) needed a convenient instrumentation system to verify parachuted pallet rigging configuration designs prior to use by operational forces. They also needed to instrument personnel being dropped via parachute to determine why dangerous swinging oscillations occur and to determine how variations of weight and wind affect the landing positions. For the paratrooper unit, the dynamics of the exit from the aircraft were not a major concern. Because of the limited space for instrumentation, a decision was made to limit the instrumentation to a small helmet-mounted antenna, a GPS receiver, and a custom-built data logger. For the paratroopers, swinging oscillations were detected by examining variations in the GPS velocity. In order for the GPS to lock on to the SV signals quickly, the receiver was fed reradiated signals while in the aircraft.

For the large cargo pallets, the attitude changes during aircraft exit are of major interest, and instrumentation size and weight are only a minor concern. Thus, a tactical grade inertial measurement unit (IMU) was used in

conjunction with the GPS to obtain a complete position and attitude profile. All processing was post-mission and a forward/backward-smoothing filter was used for the GPS data as some GPS track interrupt was expected on exit from the aircraft. Processing of the IMU data was complicated by large pitch changes (pallets frequently rotate beyond vertical when exiting), accelerations exceeding 20 g's, and the need for gyro alignment transfer. An embedded processor was used to record the data and synchronize the IMU data to GPS time.

A number of preliminary tests were made to help choose the components to use and to develop the processing algorithms. These included static tests in which the receiver was switched among spaced antennas (to simulate going from the reradiator inside the airplane to direct reception outside the airplane), dynamic tests on the freeway (including overpass outages), and tests on a motorcross track. It was found that there were significant differences among different brands of receivers in reacquiring GPS signals after exiting the aircraft. The final tests were conducted from military cargo aircraft.

INTRODUCTION

Among ABNSOTD's responsibilities is the testing of parachute deployment operations, new equipment usage, and the verification of pallet rigging configuration designs prior to use by operational forces of the United States. In order to investigate and analyze these processes, measurements of the parachute's payload behavior and dynamics during and after exodus from the aircraft were required. This is required on both palletized equipment and personnel parachutes.

The airdrop environment is incredibly stressful on both pallets and personnel, and any workable hardware data collection unit must necessarily be ruggedized. Pallet loads often receive 100 g's on landing and about 2 to 4 g's at extraction. Furthermore, the pallet units frequently rotate beyond vertical on extraction. Paratroopers experience 4 to 5 g's on exiting the aircraft and are near horizontal when the parachute opens. Figure 1 presents a diagram of the main event timeline in a pallet unit drop.

The most important data for pallets are the amount of rotation of the pallet on extraction (significant rotation beyond vertical can result in severing of some of the shroud lines) and the vertical velocity after stabilization. For the paratroopers, the most important data are the time for the parachute to cease oscillating and the vertical velocity. Round parachutes used for mass drops of paratroopers tend to be unstable, starting with a pendulum type of oscillation, which may evolve into a coning type of motion [Hoerner and Borst, 1975]. A number of design features are incorporated into the parachutes that try to mitigate this undesirable behavior. The sooner the oscillations can be halted, the lower the drop altitude can be in combat. The lower altitude reduces exposure to hostile fire of both the aircraft and the paratroopers.

Our approach to these problems was to use two separate instrumentation/data recording packages. A 10 pound aluminum-encased package with a GPS receiver and a

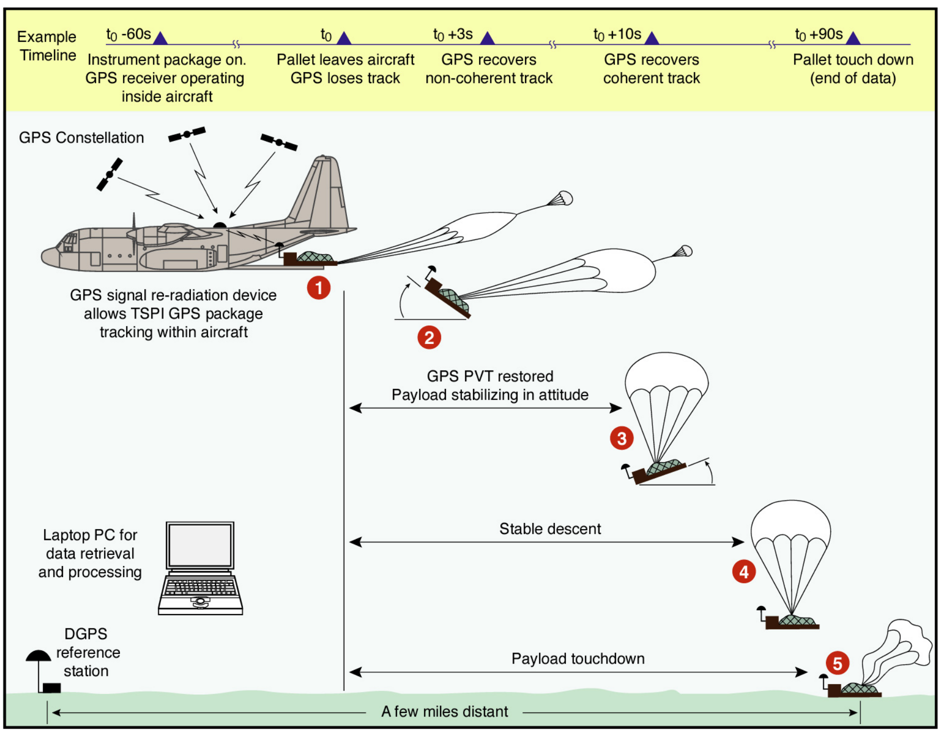

Figure 1. APLS operational concept

Litton LN200 IMU was used for the pallet instrumentation. The Airborne Position and Location System (APLS) contains a small dedicated computer that facilitates GPS/IMU timing and records IMU and GPS data. For the troopers, only a GPS receiver with a dedicated computer for recording the data was used. Oscillation analysis was derived from GPS velocity measurements for the trooper. The trooper unit, including batteries, weighs less than a pound.

In order to minimize GPS acquisition time on exiting the aircraft, we required that the GPS be allowed to acquire and track the satellites prior to exiting the aircraft. This signal access is accommodated by a GPS antenna external to the top of the aircraft. A low power reradiator is used inside so that SV signals may be acquired by the APLS package and their ephemeris data downloaded prior to exodus. On the pallet unit, the reradiated signal also serves to initialize and calibrate the IMU while it is in the aircraft. This allows for accurate tracking during the GPS outage when the pallet is extracted.

The trooper tracking presents difficulties not encountered by the pallet unit. In particular, the unit is moved and jostled on the aircraft as the individual troopers move about during the drop preparation. This frequent signal outage has caused problems with coherent track and data demodulation. Therefore, a number of laboratory, vehicle, jumping motorcycle, and aircraft tests were carried out to test and choose equipment for the instrumentation packages. For the most part, the operational conditions proved more difficult than expected based on the results of the tests.

EQUIPMENT CONSIDERATIONS TROOPER UNIT

Although a high-accuracy GPS solution was desired, the events of interest for the trooper occur within the first 10 seconds of the jump. Therefore, solutions involving GPS RTK were generally discarded as were military type PPS receivers. We considered the Ashtech G12 and the NovAtel L1 OEM3 and OEM4 receivers. SRI has experience with these receivers as well as legacy software to provide differential corrections.

The general assumption was that reradiation antennas would provide a means of tracking the GPS signals until immediately before the trooper left the aircraft. Thus, the only real reacquisition problem seemed to be that of relatively high change in Doppler on either side of the reacquisition.

In static testing in which the antenna was switched off, we found that the NovAtels reacquired most of the signals in 1 to 3 seconds for outages of 10 seconds or less. For outages of up to a minute the NovAtels took 5 to 7 seconds to reacquire a majority of the signals. The Ashtech took 4 or 5 seconds for the short outages and 5 to 7 seconds for the longer outages. In freeway tests, passing under overpasses, the NovAtel frequently kept four or more satellites in track (but not the same satellites) all the time. The Ashtech usually took from 5 to 7 seconds to reacquire most of the satellites.

One test that was done to simulate the receiver going from a reradiated environment in the airplane to the open environment was to place two antennas on the roof about 10 meters apart and switch the receiver from one to the other in about 10 ms. This time interval was considered to be the nominal time that the unit would not be able to see satellites. Both receivers performed well, settling on the correct solution within two seconds.

A second test was done to test reacquisition with significant velocity changes. A light aircraft was flown to the north at about 90 knots. The antenna was switched off just as a rapid turn to the south was begun. The turn was completed in less than 10 seconds and the antenna was reconnected. Receiver recovery of most of the SVs occurred in about 7 seconds, about the same time as for a stationary receiver subject to the same outage.

The GPS receivers are also sensitive to shock and vibration. Simply holding the receiver in hand and shaking it can prevent it from reacquiring the GPS signals if the signals are lost because of an obstruction. The receiver was also tested on a motorcross (specialized jumping motorcycles) track. On landing after a 15 foot drop onto a sloped ramp, the receiver invariably lost track of all SVs. The motorcycle has 12 inches of suspension travel—although not all of it is used on this medium sized jump, and the rider's legs also provide additional cushioning. The trooper unit with the receiver was attached to the rider's waist, and the antenna was on his helmet.

Generally, both receivers seemed to perform similarly. The Ashtech G12 was chosen largely because of the lower power consumption, slightly smaller form fit, and reputation for working under high acceleration.

TROOPER UNIT DESIGN

Figure 2 shows the trooper unit. The Ashtech G12 GPS receiver is a 12-channel, single frequency CA code and carrier GPS card developed. The G12 uses an L1 antenna and a low-noise amplifier (LNA). The G12 is rated to track through 20 g's and has a programmable tracking loop bandwidth. The receiver is commanded to try to steer its clock to GPS time and all references are related to the WGS 84 ellipsoidal system. A block diagram of the trooper unit is shown in Figure 3.

Figure 2. The trooper instrumentation package.

The project's data capture requirement is for 10 Hz. This required the high output rate model of the G12. For data instrumentation we capture the Missile Application Condensed Measurement Record (MACM). The message can be output at 20 Hz and was designed for high-speed data output under limited bandwidth conditions common to high dynamic telemetry. Satellite PRN, Doppler, pseudo-range and full carrier phase are contained in the message [Haas, 2000]. Unfortunately, the MACM contains no noise statistics and the pseudo-range used contains little or no smoothing. Therefore, we used an azimuth-dependent set of pseudo-range weights. Also, the relatively high data capture rate causes a high velocity noise that we smooth in post-processing.

EQUIPMENT CONSIDERATIONS: PALLET UNIT

The main requirement for the APLS unit components were their ability to withstand the high g impact. The required angular rate capability of the gyros was set at 180 degrees/s. To verify the unit's resistance to shock, it was attached to a pogo stick, lifted to 8 feet and dropped. This generated a measured 45 g's and was useful for initial component verification.

In order for the IMU to be fully calibrated in the aircraft, and for the GPS receivers to have almanacs and ephemerides, a GPS reradiator system is temporarily installed in the aircraft. It consists of an antenna placed in a small port in the top of the aircraft, an L1 band amplifier and an antenna to broadcast the GPS signals inside the aircraft. It is similar to reradiators used at ION-GPS conventions to allow signals to be received inside a metal roofed display hall.

PALLET UNIT DESIGN

The APLS pallet instrumentation package (Figure 4) is a self-contained unit with a GPS receiver, antenna, a Litton LN200 IMU, an SDLC (Synchronous Data Link Control) board, a CPU card, flash memory, and a battery pack for two hours of operation. Ports for a remote antenna and an external battery for longer operating times are also provided. The package weighs a bit over 10 pounds and is about 8 inches long. As there is no requirement for real-

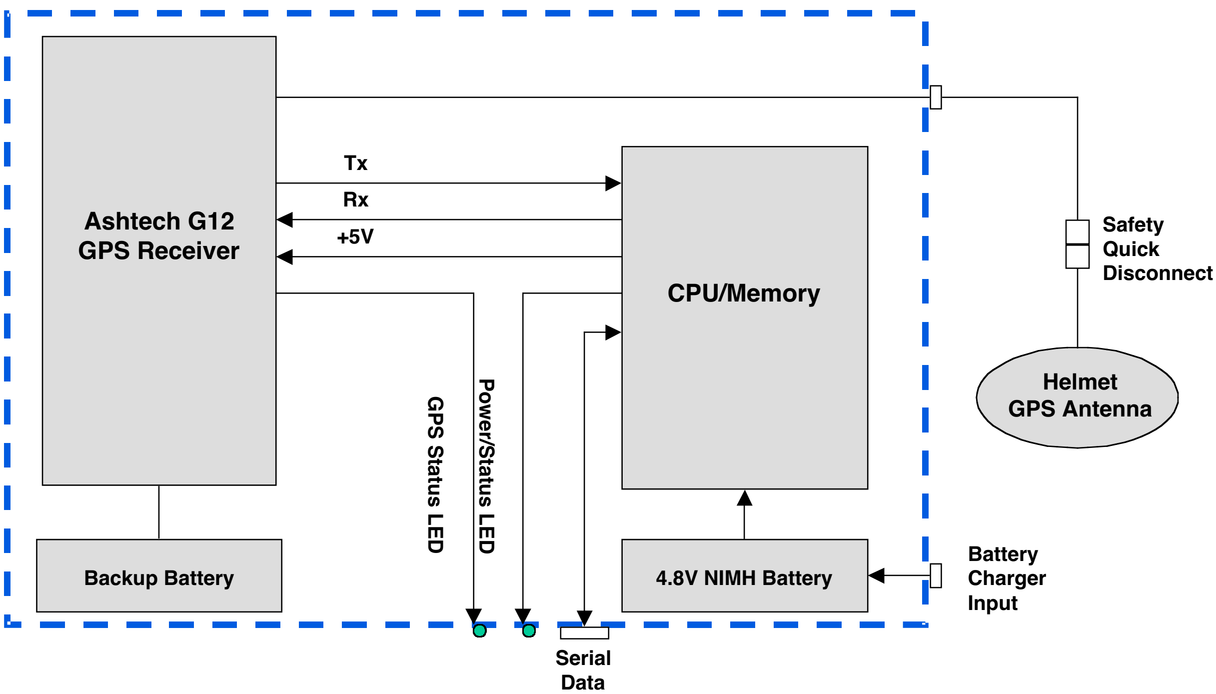

Figure 3. Block diagram of the trooper instrumentation package.

Figure 4. The APLS pallet instrumentation package.

time information, data are processed after the drop. To maintain constant temperature, a smart fan and power supply were added.

The 100 Hz IMU data are time tagged to within 200 μs of GPS time using a high-speed timer. As there is no requirement for real-time information, data are processed after the drop. However, the data collection scheme has been run on a 200 Hz unit without glitches and other evidence indicates that under 20 percent of CPU time is being used. Further details on the APLS unit can be found in Strus et al. [2002].

INERTIAL NAVIGATION

The moment of interest in the pallet drop is shortly after pallet egress and is a time of no GPS coverage. To provide position, velocity, and attitude at these times then requires a continuous means of navigation. A strapdown inertial measurement unit was chosen to provide navigation information during the initial GPS outages as well as any other GPS outage encountered on the way down. An IMU measures force and angular change over the sample period, which for the particular model chosen is 10 ms. The IMU has three silicon accelerometers and three single-axis fiber-optic gyros. Strapdown refers to the fact that the sensor triad is fixed to the vehicle. A software process called the navigation processor then integrates these measurements according to Newton's laws to provide change in position, velocity, and attitude over the integration interval.

Since the navigation processor uses an integration process, initialization of the navigation processor is required. Initialization is the process of seeding the navigation processor with the initial position, velocity, and orientation of the pallet unit. In general, attempts at obtaining a reasonable azimuth measurement of the unit in the aircraft were discarded.

Several different approaches to the initial alignment problem were considered. One idea to address the initial alignment problem was that of backward processing. In this scheme, the unit would be initialized after the drop on the ground. Here, since the crews tend to require access to the pallet immediately after impact, the most likely means of azimuth alignment would be another sensor, or GPS attitude, which, given the baseline size provides "instantaneous" access. Inertial navigation and Kalman filtering would then proceed backward. This scheme has the advantage that it requires GPS in the aircraft only near the point of egress. However, the g's from the landing proved larger than expected, and both the accelerometers and gyros were overflowed at impact. Thus, any attempts to navigate through the landing would be severely distorted by the incorrect information.

Ultimately, a method for more or less continuous GPS coverage was found based on a GPS reradiator. This means that we have continuous GPS coverage from unit turn on time, which is generally shortly before engine turn on. Once we have reliable GPS fixes, we could attempt to provide an initialization as well as a calibration over the aircraft flight to the drop zone. Thus, a Kalman filter was chosen to provide azimuth alignment.

The inertial navigation algorithms are divided into several parts. The coarse alignment is designed to run at the beginning of the run. After an alignment period, new INS measurements are processed by the navigation processor.

Coarse Alignment

The coarse alignment state of the filter is designed to last for six seconds. In general, it is considered an operational requirement that the unit be nominally stationary at turn on time. However, it appeared that there may be times of either user error (user forgot power on), or simply that the unit was being excessively vibrated at turn on time. After the averaging, the filter is initialized by a latitude-dependent standard deviation for azimuth and the filter begins processing new GPS measurements when available.

Fine Alignment

Since the operation of the unit is beyond our control during a mission, there is really no separate fine alignment by means of an extended gyro-compass or other means. Therefore, after coarse alignment, we immediately begin processing new measurements in the Kalman filter.

INERTIAL NAVIGATION MECHANIZATION

The inertial navigation mechanization is based on a direction cosine implementation where the primary navigation frame is the wander azimuth frame. The wander angle frame is nominally east, north, up, and the horizontal frame is offset by the wander angle. The inertial navigation algorithm task receives raw data from the IMU and scales it depending on the exact model of the IMU in use. SRI has used several different models of the LN-200. After scaling, the bias compensation is applied and then the inputs are passed to the strapdown navigator.

The navigator does an attitude update based on the direction cosine implementation of the equation

$$C_i = C_{i-1}(I + \Delta\Theta_n + 1/2\Delta\Theta^2 + \ldots) \ ,$$

where $\{\Delta\Theta\}$ is the rotation matrix of the body frame with respect to the navigation frame [Ignagni, 1990].

The nav frame velocity update is accomplished by discrete integration of the equation

$$\dot{v}_N = a_N + g_N - (w^N_{EN} + 2w^N_{IE}) x v_N$$

where v_N is the nav frame velocity, a_N is the applied force in the nav frame, g_N is the gravity compensation in the nav frame, and w^N_{EN} and w^N_{IE} are Coriolis and earth rate compensations, respectively [Savage, 1997].

Position update is accomplished by integrating the velocity increments using the appropriate earth radii. This generally seems to be more accurate than transport rate integration.

KALMAN FILTER

The extended Kalman filter was chosen as the method of sensor integration. Because of the high-rate nature of the INS data, the navigation processor output is used to provide a reference trajectory for an extended Kalman filter. The filter then processes errors in the system as well as estimates INS sensor errors.

There are two generic GPS/INS integration schemes generally considered today: one based on feeding the GPS position to the filter (which we will call solution based, but is sometimes called loosely coupled), and the other feeds individual satellite measurements to the filter (which we will call measurement based, but is sometimes called tightly coupled[1]). In the solution-based mode, the GPS and INS are treated as separate navigation processes, and generally, the GPS position and/or velocity is used as input to the filter. The GPS position/velocity output is typically derived either by a separate Kalman filter or by a least squares type algorithm. In the measurement-based mode, the GPS pseudo-range/delta-range and raw INS measurements are inputs into the filter.

[1] Other authors reserve the term tightly coupled to systems in which the IMU measurements are used to control tracking loops in the GPS receiver.

For the APLS data processing, the solution based filter was chosen largely because of the simplicity and independence from the GPS processing task. Time constraints in the project warranted a comparatively quick integration solution as well as the fact that several other applications were to be considered. Furthermore, as work on the filter started, it was not obvious that GPS would provide tracking data. As such, an independent filter was considered the wisest course. A discussion of the relative merits of the two types of filters appears in Farrell and Barth [1999]. The time that the GPS receiver was expected to track fewer than four satellites was expected to be minimal. Furthermore, the correlated noise characteristics are somewhat compensated by the longer time allowed for calibration. In general, the noise characteristics used was larger than expected. Outage times of 10 seconds or so were considered maximal.

There are 15 states in the Kalman filter.

Kalman Filter States	Number of States
Position errors	3
Velocity errors	3
Tilt errors	3
Accelerometer bias	3
Gyro bias	3

The dynamic error modeling state vector characteristics are similar to the approach of Farrel and Barth [1999]. An overview of the dynamics equation is

$$\begin{bmatrix} \delta\dot{\rho} \\ \delta\dot{v} \\ \delta\dot{\omega} \\ \dot{\beta}_a \\ \dot{\beta}_g \end{bmatrix} = \begin{bmatrix} F_{11} & F_{12} & F_{13} & 0 & 0 \\ F_{21} & F_{22} & F_{23} & F_{24} & 0 \\ F_{31} & F_{32} & F_{33} & 0 & F_{35} \\ 0 & 0 & 0 & F_{44} & 0 \\ 0 & 0 & 0 & 0 & F_{55} \end{bmatrix} \begin{bmatrix} \delta\rho \\ \delta v \\ \delta\omega \\ \beta_a \\ \beta_g \end{bmatrix} + \begin{bmatrix} \eta_\rho \\ \eta_v \\ \eta_\omega \\ \eta_a \\ \eta_g \end{bmatrix} ,$$

where $\delta\rho$ is the position error, δv is the velocity error, $\delta\omega$ are the tilt errors, and β_a and β_g are the residual INS accelerometer and gyro biases, respectively. The details of the sub-matrices are omitted here except to note that the F23 sub-matrix is given by

$$\begin{bmatrix} 0 & f_D & -f_E \\ -f_D & 0 & f_N \\ f_E & -f_N & 0 \end{bmatrix} ,$$

where f_N, f_E and f_D are the north, east, and down forces. These values are smoothed over the Kalman filter update interval and allow visibility into the azimuth errors of the system given horizontal accelerations.

The measurement update/gain calculation is computed at every new measurement from the GPS processing task (nominally 10 Hz). The measurement consists of east, north, down position errors compensated for lever arm and timing discrepancies between the IMU and GPS. The GPS processing provides the measurements with a standard deviation that is used for the R matrix calculation.

DGPS IMPLEMENTATION

Both pallet and trooper implementations collect raw pseudo-range and carrier phase measurements. In the post-processing, these measurements are corrected via a set of SRI developed differential correction algorithms [Blackwell, 1986]. The measurements are collected from a nearby dedicated L1 GPS receiver.

FIELD TESTING TROOPER UNIT

Figure 5 shows the descent path of a paratrooper. The receiver required seven seconds to reacquire enough GPS satellites to find position. The reliability of signal acquisition has been more of a problem with troopers than with the pallet unit. This is partly due to the troopers taking off the patch antenna and relying on reradiator antenna prior to jumping, and partly due to head movements while descending. The vertical velocity of the jumper is shown in Figure 6.

In the aircraft, the reradiator has not provided consistent tracking of the GPS satellites. This is thought to be due to multipath or nulls in the standing wave pattern in the aircraft, a long metallic tube.

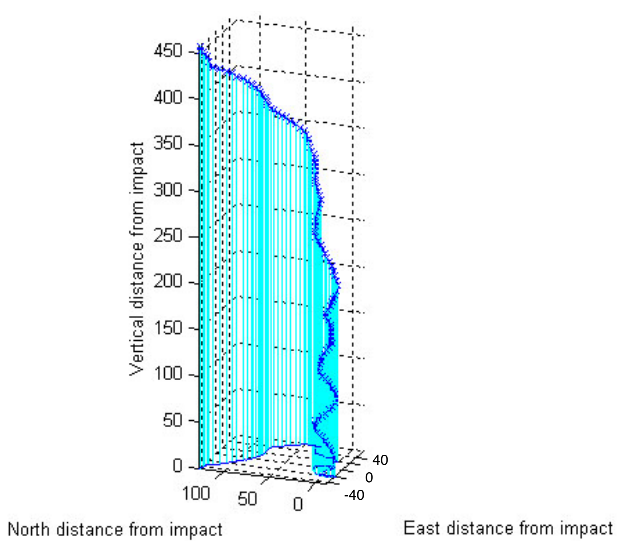

Figure 5. Descent path of a trooper.

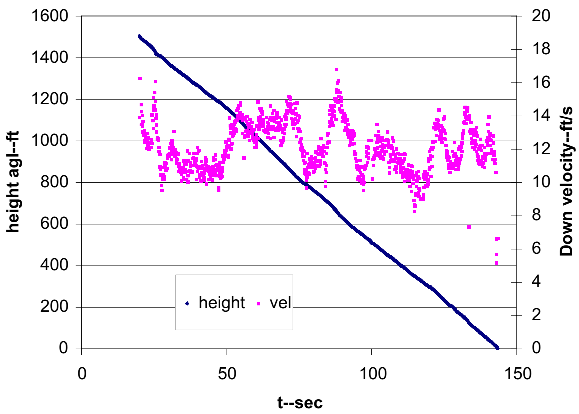

Figure 6. Height and descent rate of a trooper (units in feet and feet/s).

PALLET UNIT TESTS

Pallet unit testing began with bench testing where timing issues were resolved, basic operational issues were considered, and algorithm debug was done. Finally, we did extensive testing of the unit mounted in a minivan. These used tests L1/L2 receivers in the minivan to test the solution centimeter level accuracy RTK GPS. With two L1/L2 antennas and receivers on the van we also had GPS heading to check the heading derived by the filter. We also did tests in which we fed the filter RTK data (see Sinko and Strus [2002]).

The first tests of the pallet unit at Ft. Bragg resulted in data loss because the computer crashed on landing. Independent accelerometers on the pallet load (a vehicle) measured landing accelerations of 26 g's. Software modifications were made so that data could be recovered even if the computer crashed. Subsequent drops on a pallet with fuel cells recorded 100 g's, and the computer worked. The APLS package was not mounted on any sort of springs or vehicle suspension for this drop. One thought was that the bouncing of the vehicle suspension was responsible for the computer crashes on the first drops, but testing on a pogo stick with a 7.9 foot drop gave 45 g accelerations, lots of bounce, but no computer failures. Nevertheless, for most tests we have mounted the unit to the pallet itself rather than to any vehicle on the pallet.

Figure 7 shows the path of a pallet load with six parachutes. Figure 8 shows the differences in height measurements between the APLS unit and a Contraves video tracker/laser rangefinder system (VTS). The differences are within the measurement accuracy of the VTS. Vertical velocity measurements from the APLS unit are shown in Figure 9. When the pallet is pulled from the aircraft by the parachutes it begins an almost vertical fall, ending in a swing to level and then stabilizes in vertical speed. This can also be seen in Figure 10, which shows the pitch of the pallet. Figure 11 shows the applied force components. In this case the exit forces were modest.

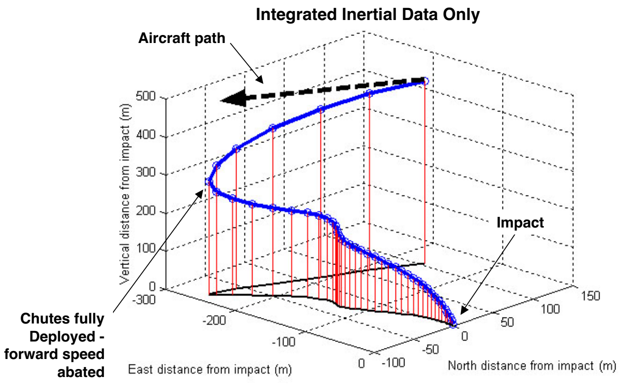

Figure 7. Three-dimensional path of a pallet drop.

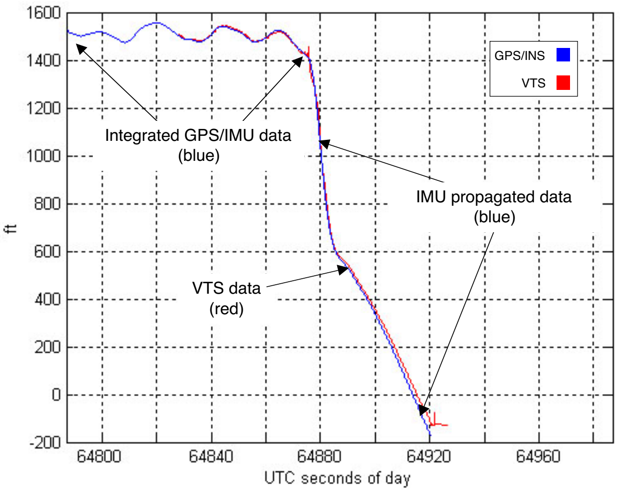

Figure 8. Altitude as measured by APLS pallet unit and the VTS.

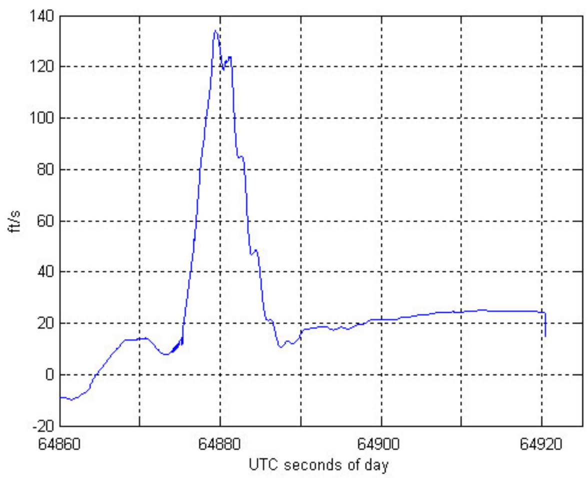

Figure 9. Descent speed of a pallet (IMU data only).

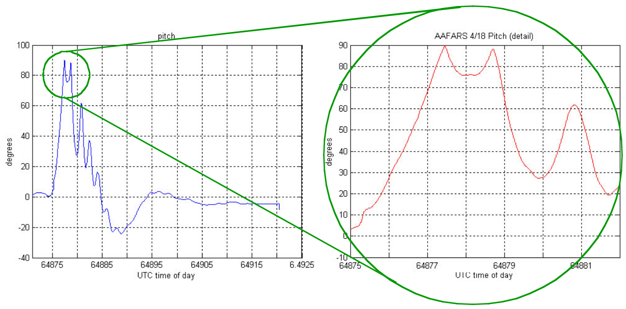

Figure 10. Pallet pitch. Detail shows the pallet pitching beyond vertical. Our definition of pitch is angle from the horizontal plane.

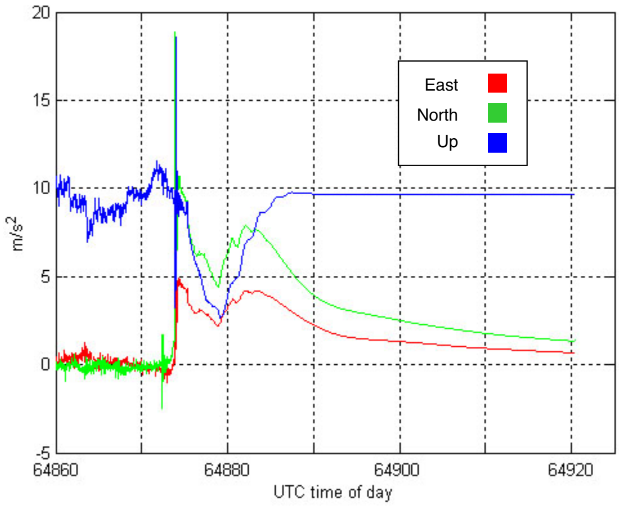

Figure 11. Measured applied force components.

CONCLUSIONS

The APLS pallet unit is able to perform all tests required to verify that the test configuration of pallet rigging is proper. The unit is fully self contained. The IMU is good enough that acquiring good GPS tracking in the first few seconds is not critical. In fact, the Kalman filter calibration of the IMU is good enough that all essential data can be obtained even if GPS is not reacquired at all before landing. Reradiation directly to the APLS unit antenna inside the airplane worked well.

The use of GPS to test personnel chutes provides a convenient way of gathering swing data and rate of vertical descent. The one weakness of this approach is that the GPS is not available for at least 5 or 10 seconds after exit from the aircraft, so parachutes with short stabilization times cannot be measured.

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