Chapter 2 – AIRCRAFT NAVIGATION TO A PRECISION AIRDROP OVERVIEW

This chapter discusses the procedures and algorithms used by the U.S. in navigating an aircraft to perform an airdrop. These are given in U.S. Air Force Instruction (AFI) 11-231, *Computed Air Release Point Procedures (CARP)*. [1] This paper describes the C-17 automated process as used by the USAF. The airdrop navigation methods used by other USAF aircraft are described in Annex B.

2.0 NAVIGATION

The C-17 aircraft has an automated capability for the navigation part of the precision airdrop process. Precision airdrops from the C-17 aircraft are conducted using CARP, high-altitude release point (HARP), or low-altitude parachute extraction system (LAPES) algorithms. This automated airdrop process considers ballistics, winds, release location computations, time-to-go cues, and recording key data at release.

For low-altitude airdrops in which the recovery system is deployed in conjunction with the load exit, CARP is used. For high-altitude airdrops, HARP is used. Note that the difference between CARP and HARP calculations involves the trajectory during the freefall stage of a high altitude airdrop.

The C-17 Mission Airdrop Database contains the ballistics of various types of loads such as personnel, containers, or equipment and their associated parachutes. The computers allow ballistics information to be updated and displayed at any time. The database maintains the parameters shown in table 1 as inputs to ballistics computations made by the aircraft mission computer. Note that the C-17 allows ballistics to be maintained not only for discrete personnel elements and discrete equipment/cargo elements, but also combination elements of people exiting the aircraft with their equipment/cargo.

Table 1: Mission Airdrop Database, Ballistics

Input Data Name	Description
Location Element Exit	Where the element will exit the aircraft
Location Element Exit Combination	Where the element (combination of people and equipment) will exit the aircraft
Pressure Barometric Drop Zone Surface	Atmospheric Barometric pressure at the drop zone
Quantity Chutes Drogue	Number of drogue chutes per element
Quantity Chutes Extraction	Number of drogue chutes per element for a parachute extraction from the aircraft
Quantity Chutes Main	Number of main chutes per element
Quantity Elements	Number of discrete elements that will exit the aircraft
Quantity Elements Combination	Number of discrete elements (combination of people and equipment)
Station Number Element Center of Gravity	Where the element cg is located by aircraft station number
Station Number Element Center of Gravity Combination	Where the combination element cg is located by aircraft station number
Type Chute Drogue	Type of drogue chute employed with the element
Type Chute Extraction	Type of extraction chute employed with the element
Type Chute Main	Type of main chute employed with the element
Type Chute Main Combination	Type of main chute employed with the combination element
Weight Element	The weight of the element
Weight Element Combination	The weight of the combination element

Based on the inputs from the Mission Airdrop Database (table 1) the mission computer software computes these ballistics outputs for use in further continuous calculations of air release point, shown in table 2.

Table 2: Ballistics Computation Outputs

Output Data Name	Description
Distance Element Forward Travel	Horizontal distance travelled by the element after release
Distance Element Forward Travel Combination	Horizontal distance travelled by the combination element after release
Distance Vertical Actuate-Deploy	Vertical distance (altitude difference) from element chute actuation to full chute deployment
Distance Vertical Stability	Altitude difference from release point to point where element is under stable descent
Distance Vertical Stability Combination	Same as above, only element is combination of personnel and equipment/cargo
Time Element Exit (TEE)	Time to exit for the element
Time Element Exit Combination	Time to exit for the combination element
Time Forward Travel (TFT)	Total time the element travels forward under inertia from aircraft velocity (sum of TEE and TFTD)
Time Forward Travel Combination	Total time the combination element travels forward under inertia from aircraft velocity, after release
Time Forward Travel Deceleration (TFTD)	Time the element travels forward under inertia from aircraft velocity, after exit from aircraft
Time Forward Travel Deceleration Combination	Time the combination element travels forward under inertia from aircraft velocity, after exit from aircraft
Time of Fall Constant	Constant for particular element; time from drop altitude to stabilization altitude
Time of Fall Constant Combination	Constant for particular combination element; from drop altitude to stabilization altitude
Velocity Down Deployed	Downward velocity of the element under deployed chute
Velocity Down Deployed Combination	Downward velocity of the combination element under deployed chute
Velocity Down Free Fall	Downward velocity of the element during free fall (for a HARP computation)

2.1 WINDS

After the airdrop load is released, winds affect the direction of travel and time of fall. The C-17 mission computer computes winds using data from the aircraft's various airspeed, pressure, and temperature sensors, as well as navigation sensors. Wind data may also be entered manually using information from the actual drop zone (DZ) or from weather forecasts. Each type of data has benefits and drawbacks. Aircraft sensor winds are very accurate but may not reflect the weather conditions over the DZ because the aircraft is not able to fly from the ground to altitude over the DZ. Ground wind data are usually not the same as winds at altitude, particularly at high altitude. Forecast winds are predictions and do not reflect wind speeds and direction at the different altitudes. Actual wind profiles are usually not linear versus altitude. If the actual wind profile is not known and entered into the mission computer, the default assumption of a linear wind profile adds to errors in CARP computation. After those computations are made (or data entered), their results are written to the Mission Airdrop Database (table 3) for use in further computations of the CARP, or HARP, based on mean effective winds (MEW). Winds are not used for LAPES releases, since the aircraft releases cargo just above the ground at the desired point of impact (PI). The C-17 mission computer

calculates the net along-track and cross-track offset components of wind drift distance for CARP and HARP airdrops. Wind drift distance is a function of average wind velocity and drop element total time of fall as may be seen in the equations following table 3.

Table 3: Mission Airdrop Database, Winds

Input Data Name	Description
Velocity Wind	Wind velocity computed by navigation systems based on heading, airspeed, ground track, etc
Velocity Wind Airdrop Altitude	Wind velocity at the aircraft airdrop altitude
Velocity Wind Ballistic	Wind velocity for period of element travel in ballistic (no chute) configuration
Velocity Wind Chute Deployed	Wind velocity for period of element travel under deployed chute
Velocity Wind Mean Effective	Mean wind velocity vector computed from airdrop altitude to PI
Velocity Wind PI	Wind velocity on the ground at PI

2.1.1 CARP Winds Equations

$$\text{Distance Along Track Wind} = MEW_{ALONG} \text{ X Total Time of Fall}$$

$$\text{Distance Cross Track Wind} = MEW_{CROSS} \text{ X Total Time of Fall}$$

$$\text{Total Time of Fall} = \text{Time to Stabilization} + \text{Time from Stabilization to PI}$$

$$\text{Time from Stabilization to PI} = \text{Altitude Chute Stability / Adjusted Rate of Fall}$$

The values for the above terms are determined as follows:

$$\text{Altitude Chute Stability} = \text{Altitude Above Drop Zone} + \text{Elevation High Point Air Drop Zone} - \text{Elevation PI Air Drop Zone} - \text{Distance Vertical Stability}$$

$$\text{Adjusted Rate of Fall} = \text{Rate of Fall}_{DEPLOYED} \text{ X Air Density Correction Factor}_{DEPLOYED}$$

Rate of Fall is entered, preloaded, or computed using ballistic data as Velocity Down Deployed (see table 2).

Air Density Correction $\text{Factor}_{DEPLOYED}$ is determined at the average drop pressure altitude and the average temperature in the vertical region bounded by the PI elevation and the drop altitude.

2.1.2 HARP Winds Equations

A two-stage model is used to calculate wind drift for HARP air releases. The total wind drift is the sum of the drift encountered in the free-fall, high-velocity stage and the drift encountered during the high-drag, chute-deployed stage.

$$\text{Distance Along Track Wind} = \text{Distance Along Track Wind}_{HIGH\ VELOCITY} + \text{Distance Along Track Wind}_{HIGH\ DRAG}$$

$$\text{Distance Cross Track Wind} = \text{Distance Cross Track Wind}_{HIGH\ VELOCITY} + \text{Distance Along Track Wind}_{HIGH\ DRAG}$$

2.1.2.1 HARP Free-Fall, High Velocity (HV) Stage

Distance Along Track $Wind_{HV}$ = Velocity Wind $Ballistic_{ALONG}$ + Total Time of $Fall_{HV}$

Distance Cross Track $Wind_{HV}$ = Velocity Wind $Ballistic_{CROSS}$ + Total Time of $Fall_{HV}$

Total Time of $Fall_{HV}$ = Time to Stabilization + Time From Stabilization to Actuation

The wind drift component of the time of fall from aircraft exit to stabilization is entered, preloaded, or computed from ballistic data as Time of Fall Constant (see table 2).

Time from Stabilization to Actuation = [(Altitude Chute Stability – Altitude Indicated Chute Actuation) / Adjusted Rate of $Fall_{HV}$] + Time Delay Chute Actuation

The values for the above terms are determined as follows:

Altitude Chute Stability = Altitude Pressure at Release Point + Altitude Difference True / Pressure – Distance Vertical Stability – Elevation PI Airdrop Zone

Adjusted Rate of $Fall_{HV}$ = Rate of $Fall_{HV}$ x Air Density Correction $Factor_{HV}$

Rate of Fall is entered, preloaded, or computed from ballistic data as Velocity Down Free Fall (see table 2).

Air Density Correction $Factor_{HV}$ is determined at the average drop pressure altitude and the average temperature in the vertical region bounded by the actuation altitude and the drop altitude.

2.1.2.2 HARP High Drag (HD), Chute-Deployed Stage

The second stage of a HARP air release begins at parachute actuation and ends at ground impact. This region is characterized by high drag as the parachute system is fully deployed. The second stage of the HARP air release is identical to that of the single-stage CARP release except for the initial high downward velocity of the drop element resulting from the HARP first-stage free fall.

Distance Along Track $Wind_{HD}$ = Velocity Wind $Ballistic_{ALONG}$ + Total Time of $Fall_{HD}$

Distance Cross Track $Wind_{HD}$ = Velocity Wind $Ballistic_{CROSS}$ + Total Time of $Fall_{HD}$

The values for the above terms are determined as follows:

Total Time of $Fall_{HD}$ = Time from Actuation to Deployment + Time From Deployment to PI

The time from chute actuation to full chute deployment is entered, preloaded, or computed from ballistic data as Time Actuate Deploy (see table 2).

Time from Deployment to PI = Deployment Altitude/Adjusted Rate of $Fall_{HD}$

Deployment Altitude = Altitude Indicated Chute Actuation – Deceleration Distance

Deceleration Distance = Distance Vertical Actuate-Deployment + (Time Delay Chute Actuation x Adjusted Rate of $Fall_{HD}$)

Adjusted Rate of $Fall_{HD}$ = Rate of $Fall_{DEPLOYED}$ x Air Density Correction $Factor_{DEPLOYED}$

Rate of Fall is entered, preloaded, or computed from ballistic data as Velocity Down Deployed (see table 2).

Air Density Correction $Factor_{HD}$ is determined at the average drop pressure altitude and the average temperature in the vertical region bounded by the PI elevation and the actuation altitude.

2.2 RELEASE POINT COMPUTATIONS

Based on the location of the desired PI, the C-17 mission computer uses ballistics and wind data as described in section 2.1 and the aircraft position, altitude, heading, and velocity to compute a point in space for the aircraft to fly to release its cargo. The C-17 aircraft is capable of flying to within 100-meter computed error probable (CEP) of the optimum air release point from which the first drop element will land at the PI.

CEP is calculated as follows [2]:

n = number of PI position data points

m = horizontal error

Geometric Mean (GM):

$$GM = \sqrt[n]{m1 * m2 * m3 * \ldots \ldots * mn\text{-}1 * mn}$$

Root Mean Square (RMS):

$$RMS = \sqrt{((\sum m2)/n)}$$

$$R = GM / RMS$$

When R > 0.42 then: $Y = -0.13R2 + 0.89R + 0.24$

When 0.02 < R < 0.42 then: $Y = 0.23R – 0.05 + 0.84R1/2$

When R < 0.02 then: $Y = 0.70R + 0.40R1/2$

$$CEP50\% = Y * RMS$$

The C-17 computations support three different modes of release: 1) CARP, 2) HARP, and 3) LAPES.

CARP. A computed air release point is obtained using MEWs applied to the ballistics of the cargo in a single stage model from airdrop altitude to the PI altitude.

HARP. A high-altitude release point is obtained using ballistic winds and deployed winds (see table 3) applied in a two-stage model that breaks the cargo fall into 1) a high-velocity, free-fall ballistic stage; and 2) a low-velocity, high-drag deployed stage.

Note: For CARP and HARP releases, the C-17 mission computer recomputes the location of the release point each time new input data are available (Recompute Airdrop in table 4). The C-17 mission computer also recomputes the predicted PI location 30 seconds prior to release based on current cross-track and track angle errors determined by the aircraft's guidance and navigation systems. The CARP/HARP forward and lateral offsets are computed and displayed on the aircraft's head-up displays (HUDs) and MFDs.

CARP/HARP Forward Offset = Distance Along Track Wind – Distance Element Forward Travel

CARP/HARP Lateral Offset = Distance Cross Track Wind

Distance Element Forward Travel is entered, preloaded or computed as follows:

Distance Element Forward Travel = Ground Speed Airdrop x Time Forward Travel

Ground Speed Airdrop is the desired track along track ground speed during release.

2.2.1 LAPES

A LAPES release point is simply a point a short distance above the runway at which the C-17 automatically deploys an extraction parachute to pull cargo out of the cargo bay. Winds are not used in LAPES release point computations. The LAPES air release point is simply the latitude and longitude of the desired PI.

Airdrop Modes (CARP, HARP, or LAPES; Automatic Release or Manual Release) and Airdrop Types (Personnel, Cargo Extraction, Container Delivery System, or Combination Personnel/Container Delivery System) are selected on the C-17 aerial delivery system (ADS) panel. The C-17 airdrop software computes the air release point location for the selected airdrop mode and airdrop type using data from the Mission Airdrop Database and navigation systems. The software then sends the airdrop location to the aircraft flight plan. The C-17 provides the aircrew steering cues on the HUD and MFD to get to the air release point. Table 4 presents inputs to the computations from the Mission Airdrop Database and navigation systems, and table 5 presents the outputs of those computations.

Table 4: Release Point Computations Inputs

Input Data Name	Description
Angle Track Error	Angular error between aircraft current track and desired track before release
Airdrop Mode	CARP, HARP, or LAPES selection on ADS panel
Airdrop Number	Descriptor used in flight plan used to index data in the Mission Airdrop Database
Airspeed Indicated at Release Point	Indicated airspeed
Altitude Above the Drop Zone	Self explanatory
Altitude Difference True/Pressure	Difference between aircraft altitude above datum and aircraft pressure altitude
Altitude Indicated at Release Point	Indicated altitude
Altitude Indicated Chute Actuation	Indicated altitude at element chute actuation
Altitude Pressure at Release Point	Self explanatory
Auto Select Sensor Mix	The C-17 software allows the operator to select the sensor sources of data for release point computations. Parameters include temperature, altitude and surface winds. Sources can be either manual input or aircraft sensors.
Cross Track Error	Distance between aircraft current track and desired track before release
Distance Trailing Edge to Red Light Point	Distance on the ground from the Red Light Point (termination of release) to the outer edge of the drop zone
Distance Point of Impact to Trailing Edge	Distance on the ground from the desired PI to the outer edge of the drop zone defined by the operator
Drop Zone Axis Airdrop Zone	Axis line along which the rectangular drop zone is oriented

Table 4: Release Point Computations Inputs (Concluded)

Input Data Name	Description
Elevation High Point Airdrop Zone	Elevation of the highest terrain in the drop zone
Elevation PI Airdrop Zone	Elevation of the PI inside the drop zone
Greenwich Mean Time	Self explanatory
Ground Speed	Self explanatory
Heading True Inertial Reference Unit (IRU)	Aircraft true heading as measured by IRU
Latitude Present Position	Aircraft latitude
Longitude Present Position	Aircraft longitude
Location PI Airdrop Zone	Latitude and longitude of the desired PI (within 10 meters CEP)
Pressure Altitude Variation	Difference between mean sea level pressure altitude and navigation standard datum altitude
Recompute Airdrop	Function which updates the release point location based on any sensed change or operator entered change in the data that drives the release point location computation
Temperature at Chute Actuation Altitude	Atmospheric temperature at element chute actuation altitude
Temperature at Drop Altitude	Atmospheric temperature at release altitude
Temperature at PI	Atmospheric temperature on the ground at PI
Temperature Static Air	Atmospheric temperature of static air as measured by aircraft sensors
Time to Green Light	Time to start of an airdrop.
Time Red Light to Drop Zone Escape	Time from termination of release to a waypoint defined as the Drop Zone Escape waypoint
Type of Airdrop	Personnel, Cargo Extraction, Container Delivery System, or Combination Personnel / Container Delivery System

Table 5: Release Point Computations Outputs

Output Data Name	Description
CARP Forward Offset	Along track distance of the release point relative to the desired PI
CARP Lateral Offset	Cross track distance of the release point relative to the desired PI
Distance Along Track PI Correction	For combination element releases, the C-17 checks to insure the PI is inside the drop zone; if not, the distance along track to move the PI into the nearest drop zone edge is computed and displayed
Distance Cross Track PI Correction	For combination element releases, the C-17 checks to insure the PI is inside the drop zone; if not, the distance cross track to move the PI into the nearest drop zone edge is computed and displayed
Distance Drop Zone Escape	Distance from PI to the Drop Zone Escape waypoint
Drift Airdrop Wind Adjusted	Aircraft drift angle based on winds
Heading Airdrop Wind Adjusted	Aircraft heading
Location PI Airdrop Zone	The updated location of the desired PI within the drop zone

2.3 TIME-TO-GO CUES

The C-17 provides aural and visual cues to the crews during the airdrop, which give the crew ‘time-to-go’ to the air release point. At the release point (time-to-go = zero), the aircraft can automatically release the cargo, or the crew may release the cargo manually, depending on the type of cargo and mode of release.

Table 6: Time-to-Go Cues

Cue	Description
Audible Warnings	Audible countdown to release at 30, 20, 10, 6, and 1 minutes; then 10, 5,4,3,2,1 seconds
Visual Time	Visual indications of time-to-go on HUD and multifunction displays (MFDs)
Green Light	Aircraft has reached release point
Red Light	Aircraft is outside release area
Green Light Warning	Audible warning that Green Light is lit
Red Light Warning	Audible warning that Red Light is lit
No Autodrop	Visible indication that expected impact location is outside a 300-yard distance from desired PI
No Autodrop Warning	Audible warning when expected impact location is outside a 300-yard distance from desired PI
Airdrop Cue Type	Horizontal and vertical steering cues (Forward and Lateral Offsets) displayed on HUDs and MFDs
Time Duration Greenlight	Usable Drop Zone Length / Ground Speed Airdrop

2.4 RECORDING RELEASE DATA

At the release point, a green light comes on to indicate that the aircraft is releasing the cargo automatically, or to give the crew the go-ahead to release manually. The green light stays on throughout the release until the red light comes on, indicating end of an airdrop or the aircraft overflying the end border of the DZ. The C-17 aircraft is capable of releasing cargo day or night at various altitudes and in various weather conditions. It is important to record the specific conditions of the aircraft at actual release. Sometimes the aircraft may be slightly out of position, or winds may have changed somewhat. The C-17 automatically records data about winds, actual aircraft position, and other parameters, giving the air and ground crews required information about the release. This automatic-record feature is known as green light processing. The green light records are listed in table 7.

Table 7: Green Light Processing

Green Light Records	Description
Altitude at Green Light	Aircraft altitude at release
Angle Drift at Green Light	Aircraft drift angle at release due to winds
CARP Forward Error at Green Light	Distance error along drop zone axis at release
CARP Lateral Error at Green Light	Distance error perpendicular to drop zone axis at release
Ground Speed at Green Light	Aircraft ground speed at release along the desired track
Heading at Green Light	Aircraft heading at release
Location at Green Light	Aircraft latitude and longitude at release
Time at Green Light	Time of release

2.5 NAVIGATION TESTING CONSIDERATIONS

Details on navigation systems test methods and procedures can be found in *Flight Testing of Radio Navigation Systems* [3] and in chapter 3 of *Introduction to Avionics Flight Test* [4]. Additional test considerations can be found in the proceedings of the multiple Saint Petersburg International Conferences on Integrated Navigation Systems [5]. Basically the general method involves flying to a specific point, such as the CARP, using specific navigation system modes, maneuvering using pitch, bank and yaw, approaching

the point from various compass headings. As the tests are conducted, the resultant spatial and temporal navigation errors are measured and tracked. This requires using a very accurate truth source.

The measurements for the required parameters, such as the time, space, and position information (TSPI), velocities, and deck angle (pitch), must be accurate. Using cinetheodolites or differential GPS is crucial for accurate TSPI data. One such system, used at the U.S. Air Force Flight Test Center as an accurate truth source, is the GPS-Aided Inertial Navigation Reference (GAINR) system.

The GAINR equipment consists of three major components: airborne equipment, data link, and ground support equipment. The airborne equipment consists of a high-dynamic GPS receiver, inertial unit, and solid state recorder. The data link transceiver is also carried by the aircraft and provides a dedicated, duplex, GPS link to the ground. The data link can support up to 25 simultaneous participants at a 10 Hz rate, provide automatic air-to-air relay capability when out of line of sight (LOS) with ground stations, and encrypt the down-linked data. Air-to-ground range has been demonstrated to 100 statute miles, with the potential for extended range using relay aircraft. The ground equipment consists of four remote data link ground stations, control/display processors, and a GPS reference receiver. Real-time aircraft trajectories can be provided to the control rooms for map displays or statistical analysis. Data can also be postprocessed to allow for additional filtering and smoothing for increased accuracy. Maximum accuracy trajectory estimates using GPS data are achieved by the incorporation of differential corrections. This method, referred to as Differential Global Positioning System (DGPS), makes use of a ground reference receiver at a known location to estimate errors and correct GPS observation data in real time and/or postflight. In real time, the corrections can either be made in the ground processing or up-linked for airborne processing. The GAINR incorporates high-rate (256 Hz) inertial sensor data with 1-Hz GPS pseudo-range and 5-Hz delta-range data into a tightly coupled/integrated system. The final TSPI products are produced by the Multisensor Optimal Smoother Estimation Software (MOSES), which employs the Carlson-Bierman factorized method in a Kalman filter/smoother. During its certification it produced position accuracies of ~1.7 meters (5.6 feet) horizontally and 2.5 meters (8.2 feet) vertically, and velocity accuracies of ~0.0038 meters per second (0.0012 feet per second).