

## Trajectory Optimization for Balloon Flight Planning

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### ABSTRACT

The recent solo transpacific balloon flight was used as a test case to evaluate multiple trajectory techniques to select different pathways based upon potential variations in balloon altitudes. Altitude changes between 3 and 8 km above ground resulted in predicted ending locations varying from the Hawaiian Islands to the Atlantic coast, after five days' travel. The method can be used to select optimum flight altitudes based upon forecast meteorological fields.

### 1. Introduction

The 17–22 February 1995 successful transpacific solo balloon flight (Moyer 1995) provides an opportunity to evaluate trajectory computational procedures. Considering the fact that trajectory methods are used extensively in the planning and execution stages of such flights (Wetzel et al. 1995), it would be interesting to evaluate if such a process can be automated to provide a variety of pathways to take advantage of the balloon's variable altitude capabilities.

Conceptually one would compute trajectories at several different altitudes. Then after some period of travel, new trajectories would be started at each of the trajectory positions, again at several different altitudes. This process could be repeated as frequently as computational resources permit. The final matrix of trajectory positions with time and altitude could be used to construct a pathway to a specific location within a specified time interval.

The method could be employed using archival data to perform a complete evaluation to select optimal seasons or starting locations. Or the computations can be performed operationally using forecast meteorological fields to guide the balloon in flight. The latter procedure depends not only upon the trajectory methodology but also upon the quality of the meteorological forecast as well. In this analysis only archival data will be used to demonstrate the feasibility of the pathway optimization method.

### 2. Trajectory computation method

Trajectories are computed kinematically from gridded wind fields assuming that a parcel passively follows the horizontal motion of the wind. The vertical

motion, or balloon altitude, is assumed to be under the control of the pilot, and the altitudes are predetermined for each calculation. The accurate simulation of a balloon flight path using such trajectory methods depends upon how closely the balloon's altitude matches that of the assumed trajectory. The precise control of altitude may vary depending upon ambient meteorological conditions (solar heating) as well as upon the type of equipment (inertia). Large variations in the horizontal wind with height increases the sensitivity of the trajectory calculation to altitude. In the next section a calculated trajectory will be compared with balloon positions recorded during a transpacific balloon flight.

Meteorological fields are obtained from global data archives maintained at the National Climatic Data Center (NCDC 1991). The archive, at a resolution of 381 km and at 6-h intervals, consists of fields of horizontal and vertical wind components, temperature, relative humidity, and height, for mandatory pressure levels from 1000 to 50 hPa.

The trajectory computational approach is a revised version of the method used by Draxler (1991). All the meteorological fields are first remapped to a terrain-following coordinate system that is defined by a normalized variable

$$\sigma = 1 - \frac{z}{z_t}, \quad (1)$$

where  $z$  is the height above ground level (AGL) and  $z_t$  represents the top of the model domain (10 km AGL for these calculations), an arbitrary height below the maximum height of the input data (50 hPa) and above the maximum height of any trajectory computation.

A parcel trajectory is computed from the time integration of the three-dimensional position vector  $S$ ,

$$\frac{dS}{dt} = \mathbf{V}(x, y, z, t), \quad (2)$$

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where  $\mathbf{V}$  is the horizontal velocity vector at a point in space and time. The integral is solved numerically through the improved Euler–Cauchy method (Kreyszig 1968):

$$S(t + \Delta t) = S(t) + 0.5 \Delta t \langle \mathbf{V}(S, t) + \mathbf{V}\{[S(t) + \Delta t \mathbf{V}(S, t)], t + \Delta t\} \rangle \quad (3)$$

where the velocity vector is represented by the average of the velocities at the initial location and time and the velocity at the first-guess position at time  $t + \Delta t$ . The velocity at a point is linearly interpolated from the values at the adjacent grid points and time periods. The integration time step  $\Delta t$  can vary between simulations and is based upon the requirement that  $u_m \Delta t / \Delta L < 0.5$ , where  $u_m$  is the maximum expected velocity and  $\Delta L$  is the horizontal grid length. Time steps can range from 1 min to 1 h. The balloon track trajectory calculations used a time step of 1 h, which is consistent with maximum winds of about  $40 \text{ m s}^{-1}$  recorded during the balloon's crossing.

The trajectory path is computed in both the horizontal and vertical directions such that the vertical integration of the position vector is computed in a manner similar to the horizontal component. The model uses the archive field of the total derivative of pressure (the vertical wind component) to compute vertical motion. However, because a balloon track more closely follows a constant pressure surface, an isobaric velocity  $w$  is defined from the definition of the total derivative such that

$$w = \frac{d\sigma}{dt} = - \frac{\left( \frac{\partial p}{\partial t} + \mathbf{V} \cdot \nabla_z P \right)}{\left( \frac{\partial p}{\partial \sigma} \right)}, \quad (4)$$

where  $p$  is pressure. The velocity is the value required to maintain a parcel on a constant pressure surface in the model's terrain-following coordinate system. Space derivatives are computed from centered differences.

### 3. Transpacific flight

Although it is not necessary to compare the model's calculation of the balloon path to the actual path, it provides a confidence limit in evaluating a model's ability to reproduce other pathways that were not taken. The balloon was launched at 1831 UTC on 17 February 1995 from the Olympic Stadium in Seoul, Korea, and recovered near Leader, Saskatchewan, Canada, at 0046 UTC 22 February 1995, a travel time of a little more than 100 h. The balloon's horizontal position was automatically reported every 30 min. However, altitude was manually and, hence, less frequently recorded. In

general, the balloon's vertical position was near 500 hPa ( $\pm 75 \text{ hPa}$ ) for most of the flight—toward the lower range in the earlier stages of the flight and toward the higher range in the later stages. The balloon's actual path and the model's isobaric computation [using a starting height of 5000 m above ground level (AGL)] are shown in Fig. 1. The model calculation was started at 2000 UTC, about 2 h after launch, after the balloon reached the initial flight altitude. Computations using the balloon's reported altitudes with time showed little variation from the constant height calculation. The final error of the calculation was about 10% of the travel distance. The model computation showed slightly faster transport during the first few days and slower transport during the last day (crosses are shown at 6-h intervals).

The meteorological conditions were quite favorable for such a flight. The 500-hPa heights for 0000 UTC 20 February, about halfway through the flight, are shown in Fig. 2. Note that the balloon track (position at map time shown by B) closely parallels the 5520-m contour located near the starting location (\*), indicating a relatively stationary pattern and hence less uncertainty in the reliability of any corresponding calculations.

### 4. Multiple pathways

The main purpose of this investigation is to determine how a trajectory computational method can be used to optimize flight planning and forecasts. In this regard the trajectory model was modified to simultaneously calculate many different trajectories and preserve their position and altitude history. In this mode the calculation was started simultaneously at three altitudes from the initial balloon starting time and loca-

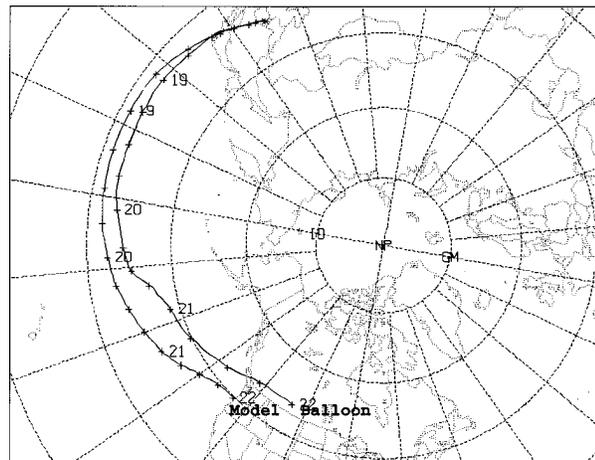


FIG. 1. Model-computed trajectory and reported balloon path for a starting time of 2000 UTC 17 February 1995. Time markings (+) are shown at 0000, 0600, 1200, and 1800 UTC with the day of the month indicated at 0000 UTC.

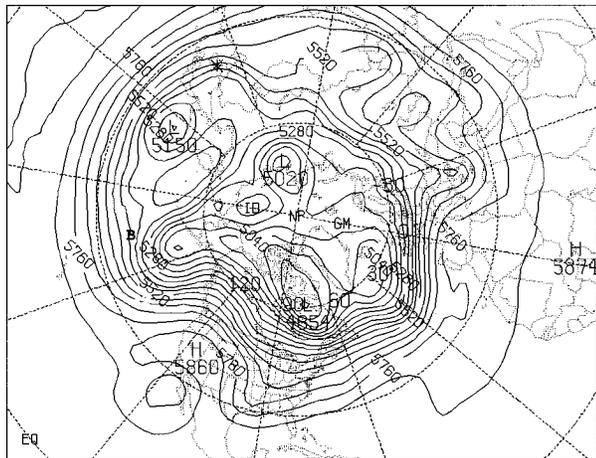


FIG. 2. The 500-hPa height contours at 0000 UTC 20 February 1995. The balloon position at that time is shown by the B.

tion. Every 24 h, two new trajectories, at the other two altitudes, would be started at each terminating location. This process is repeated every 24 h for a total calculation time of 5 days. During the last computational day, 243 trajectories are tracked.

Two different altitude variations were evaluated with computations starting at 3, 5, 7 km AGL and 2, 5, 8 km AGL. The common thread was the middle 5-km starting height, comparable to the actual balloon track. The other altitude variations may or may not be realistic possibilities given a variety of mechanical and other operating constraints. However, they provide sufficient

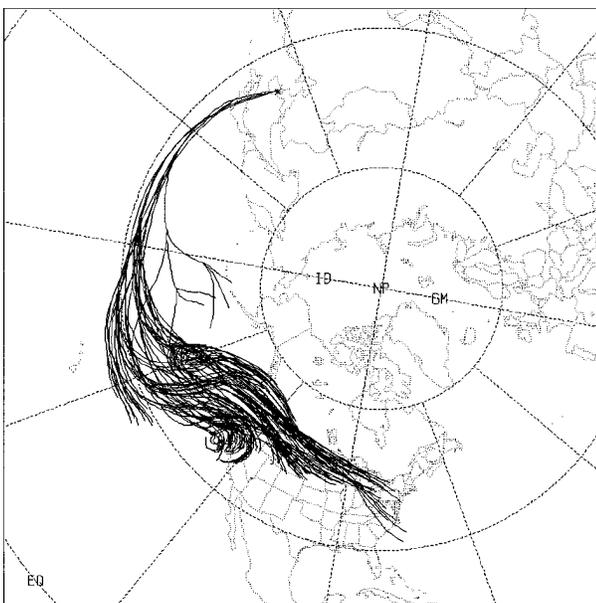


FIG. 3. Ensemble of trajectories with altitude variations at 3, 5, and 7 km AGL. Trajectories branch every 24 h.

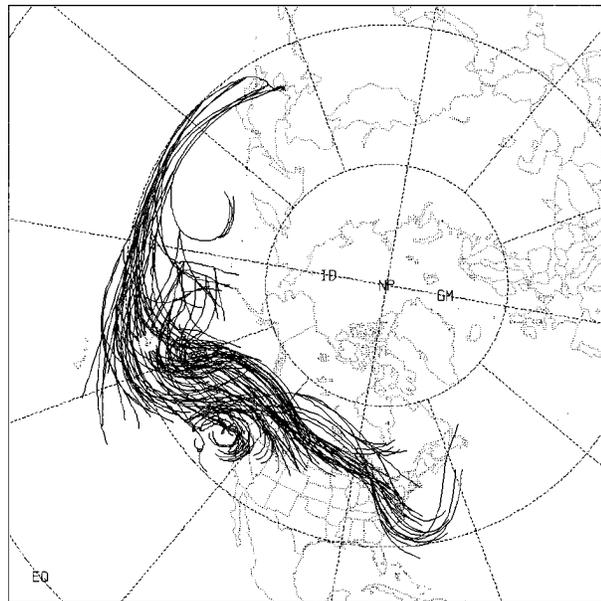


FIG. 4. Ensemble of trajectories with altitude variations at 2, 5, and 8 km AGL.

variations in the trajectory track to illustrate the methodology.

The ensemble of all trajectories for each altitude variation set is displayed in Figs. 3 and 4. The first illustration clearly shows the branching calculation technique for a group of trajectories that are moving toward the Aleutian Islands. New trajectories are

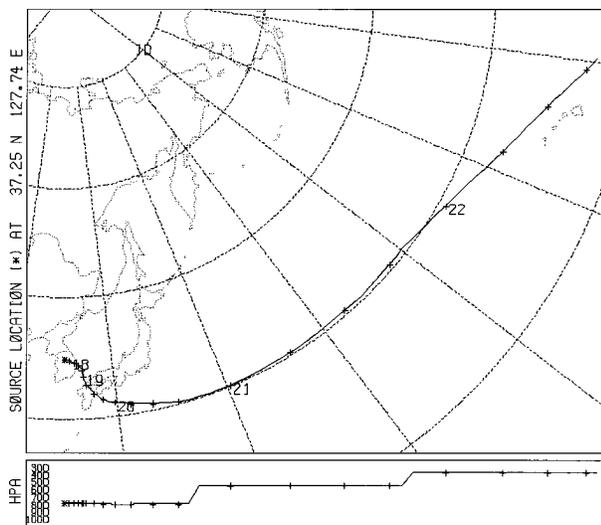


FIG. 5. Potential balloon trajectory for intercept of the Hawaiian Islands. Altitude variations are shown in the lower panel directly below the horizontal trajectory positions. Times are marked every 6 h with the day of the month shown at 0000 UTC.

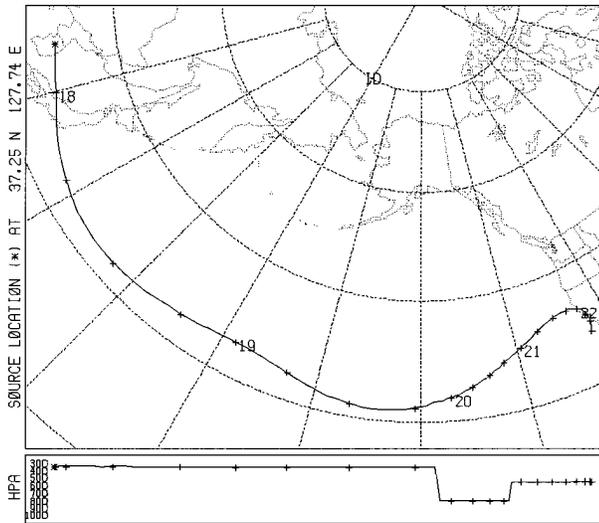


FIG. 6. Similar to Fig. 5 but showing the potential balloon trajectory to San Francisco.

started every day at 2000 UTC, at 24-h intervals after the initial starting time. All trajectories end after 5 days.

Remarkably, the trajectories shown in Figs. 3 and 4 illustrate very similar transport patterns, with the majority of trajectories making a North American landfall. In combination with the calculated result of Fig. 1, this suggests that the uncertainty in the computational path will be a fairly small component of the total trajectory variation produced by altitude changes. It is no accident that most of the trajectories at many altitudes show pathways that are favorable for a quick Pacific crossing, as this meteorological period was chosen for the balloon flight because of its well-behaved and consistent transport patterns. Some transport pathways, generally at the highest elevations, reached the Atlantic coast within 5 days, while other lower-level paths ended in the mid-Pacific.

### 5. Optimum pathway

The creation of the multiple-pathway matrix permits the selection of a particular trajectory. That is, given certain constraints, perhaps an area, or time period, one can scan the matrix to determine which combination of

altitudes provides the required solution. Figures 5 and 6 illustrate some of the possibilities. For instance the 2-, 5-, 8-km pathway combination matrix was searched for two particular trajectories, one arriving near Hawaii (Fig. 5) and one arriving near San Francisco (Fig. 6). In all cases the fastest trajectory arriving in a latitude–longitude square over the desired region was selected for display.

In addition to the horizontal trajectory path, the illustrations show the vertical projection of the path in the lower panel directly below the corresponding horizontal position. The Hawaii trajectory (Fig. 5) starts at the lowest level, moving slowly to the southeast for 2 days, and rises upward at day 3 and again at day 4 as it moves east. In contrast, the San Francisco trajectory (Fig. 6) starts at the highest level for the first day, moves to the lowest level at day 2, and then moves up to midlevel at day 3 to completion.

### 6. Summary

A simple multiple-trajectory computational procedure was demonstrated to show how meteorological data can be used to aid in complex decisions regarding atmospheric transport pathways. Simultaneous trajectories at multiple levels could be used to determine which combination of altitudes provided the trajectory path that meets certain predetermined criteria. The method provides an analytical tool to evaluate archival data for site selection and can provide operational guidance using forecast meteorological fields.

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