TRAJECTORY SIMULATION FOR SINGLE BALLOONS AND NETWORKS

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ABSTRACT

An understanding of the characteristics of trajectories of constant-altitude stratospheric platforms is important for scientific balloon flights because science observation sequences, safety planning, overflight negotiations, launch site selection, and recovery operations are affected by trajectory. Supported by NASA, Global Aerospace Corporation (GAC) has developed a Trajectory Simulation and Prediction System (TSPS) for NASA's Ultra Long Duration Balloon (ULDB) Project. We identified desirable launch dates based on historical trajectory dispersion. None of the launch sites that were studied exhibits significantly less dispersion than the other launch sites. However, latitude dispersion grows with flight duration, and trajectory dispersion growth is significant from 30- to 100-day flights. We also discuss work supported by the NASA Institute for Advanced Concepts (NIAC) where trajectory simulation techniques are applied to constellations of hundreds of balloons. We evaluate the prospects of managing the geometry of such constellations by using trajectory control systems.

INTRODUCTION

Stratospheric balloons that float at 30–40 km altitudes are an important platform for scientific and defense purposes because they fly above 99% of the atmosphere (a near-space environment), because they fly at low speeds (eliminating compression effects of sampled air), and because they float at high altitude (enabling observations of a large area of the earth). Several countries, including the United States (NASA and Air Force), France, Japan, Brazil, and others, have active stratospheric balloon programs. Recent interest in very long duration stratospheric scientific balloon flights has been stimulated by a desire to obtain high quality scientific observations from constant-altitude stratospheric platforms (Smith, 2000).

Because of the predominant stratospheric circulation pattern, balloon trajectories are characterized by zonal motion. Many stratospheric science experiments require trajectories to remain in specified latitude zones. The latitudinal dispersion characteristics of the stratospheric trajectories can be an important factor in (a) selecting launch sites and launch dates, (b) preparing safety analyses, (c) planning for payload recovery operations, (d) negotiating permission for overflight, and (e) sequencing science observations. Thus, an important parameter for mission planning is the expected trajectory excursion from the launch latitude.

To achieve minimum latitude excursion during stratospheric balloon flights, experience with short-duration flights has shown that polar summer circulation is the most favorable. In the summer, the polar vortex is typically unified, and the consistent, low-velocity, easterly (east-to-west) flight path yields little northward or southward motion. In the winter, the polar vortex typically fragments into two or more vortices, and significant disturbances (stratospheric warming events or stratwarms) can disrupt the prevailing westerly (west-to-east) flow. The twice-yearly reversal of the prevailing stratospheric winds is known as "turnaround."

In this paper, we explore long-duration (up to 100 days), stratospheric, constant-altitude (35 km), wind-driven trajectory characteristics with spatially and temporally diverse initial conditions by calculating hundreds of trajectories from launch sites at three different latitudes and 120 launch dates using historical winds. These trajectories are studied in the context of single-balloon missions and as constellations of simultaneously-flying balloons.

We begin by discussing the methods employed for trajectory simulations in this paper.

Trajectory Calculations

To assist calculation of stratospheric trajectories, we selected an environment data set which was created by the National Oceanic and Atmospheric Administration (NOAA) and the Goddard Space Flight Center (GSFC) because it provides daily, global, gridded, digital, stratospheric data over many years. We call it the "SC" data set because it was created by the method of "successive correction."

The SC data set provides environment information (including winds) near the balloon. The SC data is interpolated both spatially and temporally to obtain local conditions at points in the atmosphere. The SC data set is used as input data for calculating the trajectories that were analyzed in this study. Below, several aspects of the trajectory calculations are discussed.

To maintain consistency with the typical balloon-borne science instrument altitude requirements and typical superpressure balloon vehicle design altitudes, we assume 35 km (~ 5 hPa) as the float altitude for all balloon trajectories simulated in this study. To simulate the horizontal trajectory of balloons, we assume that the difference between the horizontal velocity components of the wind and the horizontal velocity components of the balloon is identically zero. A typical design requirement for stratospheric superpressure balloon altitude variation is $\leq \pm 1.5$ km altitude excursion during the flight. This typical altitude excursion requirement is significantly less than the vertical resolution of the environmental data set, which is about 6 km at expected float altitudes (~ 35 km).

Balloon trajectories are simulated by integrating stratospheric winds at the balloon location. We studied the effect of integration step size on the resulting trajectories, and selected the maximum step size for which increasing step size did not change the trajectory, about 1 hour.

SINGLE-BALLOON TRAJECTORIES

Using the trajectory simulation methods described above, we created a database of trajectories for various launch sites and launch dates. There are several launch sites for stratospheric balloons in the world. For the present study, we evaluated launch sites at 65° North, 24° South, and 44° South latitude, corresponding to Fairbanks, Alaska, Alice Springs, Australia, and Christchurch, New Zealand, respectively.

Launch dates were selected from a period covering the years 1981–1990. Flights originate on the first day of each month of each of the 10 years covered. The resulting trajectory database includes 360 simulated 100-day trajectories. Thus, the trajectory data set consists of 360 constant-altitude (35 km geopotential), 100-day trajectories. There are 120 trajectories for each launch site, and there are 30 trajectories for each month.

Although each trajectory begins and ends at 35 km, we refer to the starting point of the trajectory as the "launch site" for the remainder of this report. And, we refer to trajectories by the launch month, launch year, and launch location, omitting, for the sake of brevity, that each launch occurs on the first day of the month, that the flight altitude is 35 km geopotential, and that the integration time step is 1 hour.

Dispersion Characteristics

Using the trajectory database, we calculated the southernmost and northernmost excursions for every trajectory for the first 30, 60, and 100 days from launch. Figure 1 shows an example trajectory, the 100-day June 1986 Fairbanks trajectory, and Figure 2 shows the method of calculating northernmost and southernmost latitude excursions from the trajectory data. The maximum excursion for any given day is simply the greater of the extent of the northward or southward excursion.

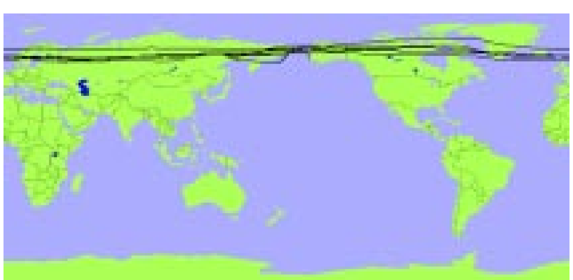

Figure 1. 100-day June 1986 Fairbanks trajectory.

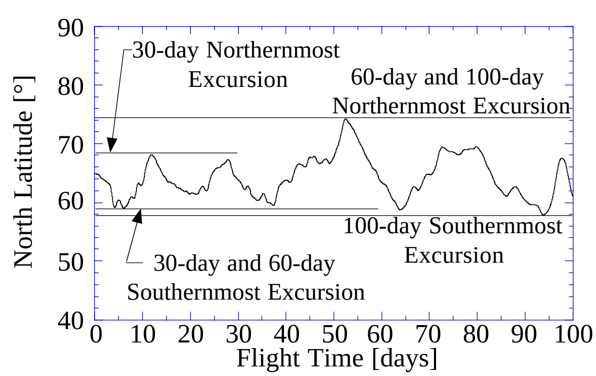

Figure 2. June 1986 Fairbanks trajectory analysis.

Fig. 1 shows a typical 100-day June Fairbanks trajectory. There is relatively little latitude excursion during the flight, consistent with the operational experience for summer stratospheric circulation patterns. Note also that near the end of the flight, turnaround conditions are observed and the flight reverses from a summer easterly to a non-summer westerly trajectory. The first 20 days of the flight are spent within a ±5° latitude band. This observation is consistent with operational experience. Fig. 3 shows the January 1986 Fairbanks trajectory, a typical winter flight that reflects less-stable winter stratospheric circulation patterns. Compared to the summer trajectory in Fig. 1, the winter trajectory does not follow summertime zonal pattern. Many reversals and loops are observed, and a polar crossing occurs.

Figure 3. 100-day January 1986 Fairbanks trajectory.

The examples in Figs. 1 and 3 suggest that (a) summer trajectories are likely to be more zonal than winter trajectories and (b) summer trajectories are less likely to exhibit significant latitude excursion. This observation is consistent with operational experience.

Launch Site Selection

For typical long-duration stratospheric scientific balloon flights, important issues for mission planning are recovery, safety, and overflight. Each of these issues is typically evaluated under the assumption that balloons maintain a "flight corridor" within a few degrees of latitude (5° to 10°) from the launch site.

Table 1 shows the percentage of database trajectories that exceed ±20° latitude excursion from each launch site. The table indicates that mission planning should be conducted assuming that significant latitude excursion (> 20°) will occur during 100-day flights. Table 2 shows the median latitude excursions from each launch site during the most favorable months at each site. None of the launch sites is observed to exhibit significantly less median latitude excursion than the other launch sites for 100-day flights. Again, the need to plan for significant latitude excursions is observed.

Table 1. Percentage of Trajectories that Exceed ±20° Latitude Excursion.

	30-day	60-day	100-day
Fairbanks (June)	11%	22%	56%
Fairbanks (July)	11%	33%	67%
Alice Springs (January)	11%	22%	67%
Alice Springs (December)	11%	56%	78%
Christchurch (January)	22%	33%	88%
Christchurch (December)	20%	50%	60%

Table 2. Median Latitude Excursions from Each Launch Site.

	30-day	60-day	100-day
Fairbanks (June)	7.2	9.4	21.0
Alice Springs (January)	10.0	11.7	29.5
Christchurch (December)	14.8	19.9	25.1

In the future, balloon trajectory control systems can reduce mission risk associated with excessive balloon trajectory latitude excursions by reducing latitude excursions for a given flight. These trajectory control systems may require real-time knowledge of forecasted balloon trajectories to effectively "steer" balloons.

Trajectory calculation and prediction methods like those demonstrated in this paper will be important for emerging trajectory control technologies.

Trajectory control systems have other potential benefits that may reduce other risks associated with very long duration stratospheric balloon flights. These potential additional benefits include “steering” to specific targets of scientific interest, reducing the risk of overflying countries with whom no international agreement exists, avoiding population centers, “steering” the balloon to designated recovery zones, and widening the set of possible launch sites for a given scientific objective. Each of these potential applications for trajectory control systems is made possible by integrating real-time forecasts of stratospheric balloon trajectories with sophisticated trajectory control system algorithms. Global Aerospace Corporation is currently extending the capabilities demonstrated in this paper to generate real-time stratospheric balloon trajectory forecasts from stratospheric environment data sources that are provided under special agreement.

TRAJECTORY SIMULATION AND PREDICTION SYSTEM

The need for real-time trajectory simulation and prediction capability is driven by upcoming very long duration missions that, by nature of their longer duration, will have additional overflight concerns and more capable and expensive payloads (Smith, 2000). Overflight issues will involve international discussions and agreements and require definitive data on balloon path predictability. (There are concerns that some countries may not offer permission to enter their airspace.) In addition, the value of future payloads is expected to be significantly higher than present payloads as the very long duration missions attract more scientific investigators. High-accuracy, in-flight trajectory simulation capabilities will assist NASA with overflight issues, safety issues, and payload recovery operations. A key element in the development of the very long duration ballooning technology is the ability to simulate and predict the trajectory of the stratospheric balloons both before and during flight.

Using the trajectory simulation technology discussed above, Global Aerospace Corporation has developed an advanced Trajectory Simulation and Prediction System (TSPS) for NASA’s scientific balloon program. The TSPS is a collection of computer system hardware, computer system software, and integrated balloon-environment trajectory simulation software. The TSPS provides in-flight predictions of stratospheric balloon trajectories from weather forecast data. Fig. 4 shows a screen shot of the TSPS. Several different models for the balloon’s vertical behavior are available in the TSPS. Fig. 5 shows the vertical model dialog box.

CONSTELLATION TRAJECTORIES

There is recent interest in developing simultaneous measurement capabilities from stratospheric platforms. Global Aerospace Corporation has been funded by the NASA Institute for Advanced Concepts (NIAC) to investigate the feasibility of and potential earth and space science uses for a network or constellation of stratospheric platforms (StratCon) (Nock, 2000). In the StratCon concept, a StratoSail® Trajectory Control System provides limited but sufficient trajectory control to maintain the geometry of the constellation as it evolves (Aaron, 1999, Aaron, 2000). In this section, we demonstrate the feasibility of maintaining a distributed geometry for a constellation of stratospheric platforms with small trajectory control capability.

Fig. 6 shows an initial random distribution of 100 stratospheric platforms (StratoSats). This distribution is used as the initial condition for all the simulations below.

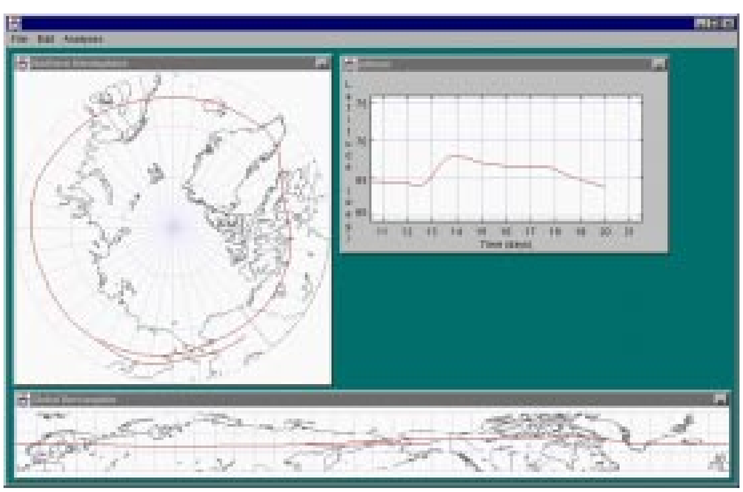

Figure 4. TSPS screen shot.

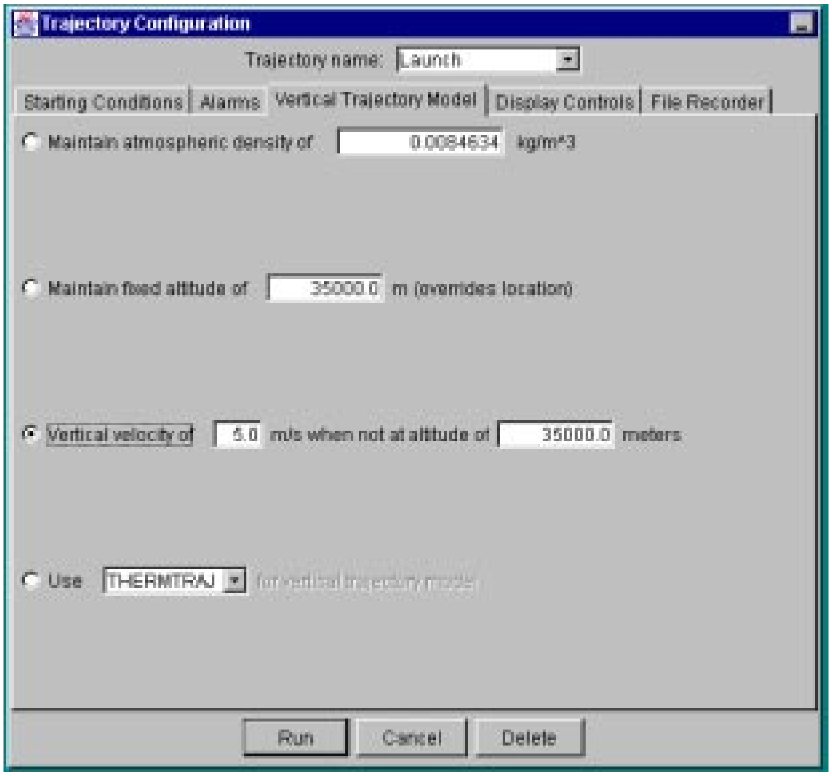

Figure 5. TSPS vertical model configuration dialog box.

Without Geometry Control

Fig. 7 shows the constellation after 82 days of simulation. Note that the location of each StratoSat is given by a dot and that three days of trajectory history are given as a "tail." Each day is marked with an arrow. After 82 days significant voids and clusters are observed, and non-uniform coverage of the globe is the result.

With Geometry Control

However, by using the StratoSail® Trajectory Control System with 5 m/s of trajectory control capability, it is possible to maintain uniform coverage of the globe. Fig. 8 shows the same network after 82 days with geometry control provided by the StratoSail® Trajectory Control System.

SUMMARY

We have developed trajectory simulation capabilities that provide capabilities to (a) evaluate balloon program and campaign decisions such as launch site and date selection, (b) conduct real-time in-flight trajectory simulation for to evaluate overflight and safety evaluation, and (c) simulate the evolution of networks of stratospheric platforms and lighter-than-air vehicles. Using those capabilities, we have evaluated launch site and launch date options for the NASA Scientific Balloon Program, developed a real-time Trajectory Simulation and Prediction System for NASA, and demonstrated that a small trajectory control capability can be used to maintain a desired geometry of a constellation of stratospheric platforms.

ACKNOWLEDGEMENTS

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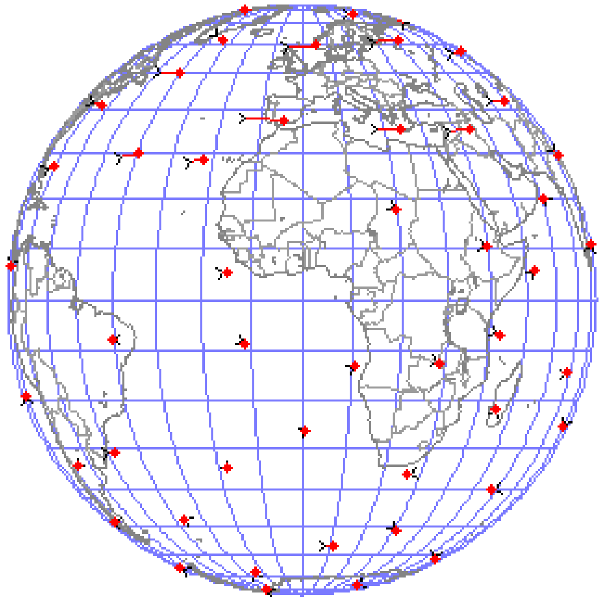

Figure 6. Initial conditions for simulations.

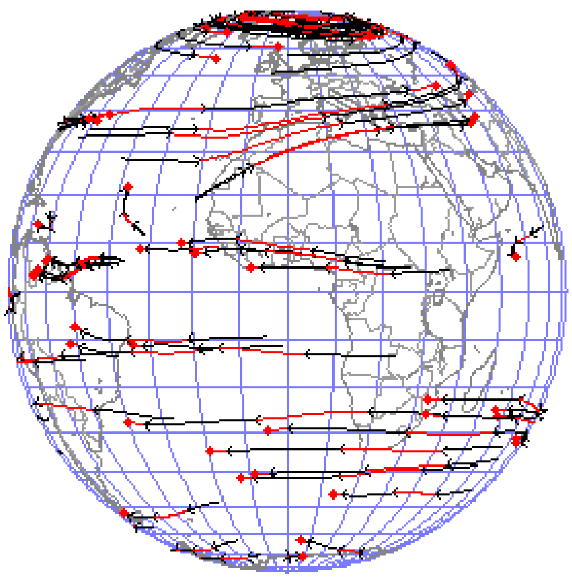

Figure 7. Without geometry control.

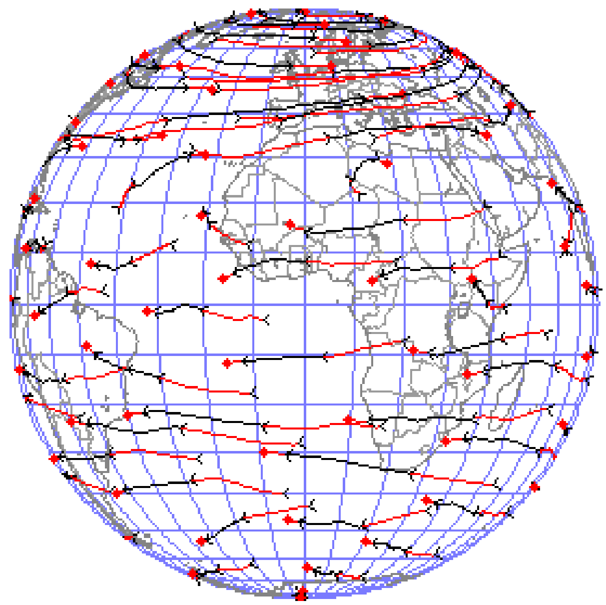

Figure 8. With geometry control.

REFERENCES

Aaron, K. M., M. K Heun and K. T Nock, Balloon Trajectory Control, AIAA paper 99-3865,AIAA International Balloon Technology Conference, Norfolk, VA, July 1999.

Aaron, K.M., K.T. Nock, & M.K. Heun. A Method for Balloon Trajectory Control, COSPAR, Paper PSB1-0012, July 2000.

Nock, K. T., M.K. Heun, & K.M. Aaron, Global Stratospheric Balloon Constellations, COSPAR, Paper PSB1-0014, July 2000.

Smith, I.S. Overview of the Ultra Long Duration Balloon Project, COSPAR, Paper PSB1-0021, July 2000.