Development of a Balloon-Borne Stabilized Platform for Measuring Radiative Flux Profiles in the Atmospheric Boundary Layer

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Introduction

A stabilized platform has been developed to carry broadband short-wave and long-wave radiometric sensors on the tether line of a small tethered balloon that ascends through atmospheric depths of up to 1.5 km. The resulting vertical profiles of radiative flux and flux divergence should prove useful in evaluating atmospheric radiative transfer models, especially for cloudy conditions where the radiative transfer codes are in an early state of development.

Our stabilized platform, called the Sky Platform, was designed to keep the radiometers level despite unpredictable movements of the balloon and tether line occasioned by turbulence and wind shear. The sky platform has a triangular frame that is carried within a three-line harness inserted into the tether line 30 m or more below the balloon. Level sensors detect when the platform is off-level. The automatic control loop drives motors, gears, and pulleys located on two of the vertices of the triangular frame to "climb" the harness lines to keep the platform level. Radiometric sensors, an electronic compass, and an on-board data acquisition system make up the remainder of the Sky Platform.

Because knowledge of the dynamic response of the tether line-platform system is essential to properly close the automatic control loop on the Sky Platform, a Motion-Sensing Platform (MSP) was developed to fly on the tether line in place of the Sky Platform to characterize the Sky Platform's operating environment. This unstabilized platform uses an array of nine solid-state linear accelerometers to measure the lateral and angular accelerations, velocities, and displacements that the Sky Platform will experience. The MSP also carries a flux gate magnetometer to measure platform heading; a data acquisition system; and, during special calibration experiments, two single-axis rate gyroscopes.

A recent paper by Alzheimer et al. (1993) describes the Sky and Motion-Sensing platforms, and a paper by Shaw and Whiteman (1993) uses a numerical radiation model to assess the engineering performance requirements of the Sky Platform stabilization system. The model, which performs angular integrations of a variety of published sky radiance distributions, estimates the irradiance measurement errors that would be produced on tilted radiometers. It also assesses the effect of oscillatory motions of the radiometer on measured irradiances.

The model shows that the most stringent requirement on radiometer leveling is encountered during clear daytime conditions. In these conditions, the mean tilt of the radiometer must be less than 1° with oscillations less than about 2° in order for the measured radiation to be accurate to 10 watts per square meter. During nighttime, or under daytime conditions when the radiation field is more isotropic, these conditions may be relaxed significantly.

This paper presents field performance tests of the Sky and Motion-Sensing platforms, as conducted at Richland, Washington, on February 17, 1993. The tests were performed primarily to characterize the stabilization system on the Sky Platform. Test flights were performed on this cold winter day from 1400 to 1800 Pacific Standard Time (PST). During this period, temperature profiles were near the dry adiabatic lapse rate. Flights were made through a jet wind speed profile having peak wind speeds of 7 m/s at a height of 100 m above ground level (AGL). Wind directions were from the northwest. All flights were continuous ascents, rather than in discrete steps with halts at set altitudes.

Sky Platform

The overall performance of the prototype Sky Platform stabilization system is presented in Figure 1 by comparing Sky Platform tilt angles on the two nominally horizontal axes from a stabilized and an unstabilized flight. The stabilized flight was conducted as a 5-minute ascent starting at 1704 PST, while the unstabilized flight was a 5-minute ascent starting at 1714 PST. The stabilization system was deactivated during the unstabilized flight, and the motors were pinned so that the platform would be horizontal if the harness system were oriented vertically. Since only small changes in atmospheric turbulence levels are expected between the stabilized and unstabilized flights, comparisons of mean and standard deviations of the tilt angles can be used to assess overall stabilization system performance.

For Sky Platform axis 1, the unstabilized performance was 19.48 ± 2.25° and the stabilized performance was 0.74 ± 1.60°. For axis 2, the unstabilized performance was 20.07 ± 1.93° and the stabilized performance was 0.82 ± 0.80°. The gain on the control loop was set somewhat too high on axis 1 during this test, resulting in higher amplitude oscillations than for axis 2, but the results show that the stabilization system is effective in keeping the platform level for accurate radiation measurements.

During two periods in the stabilized flight, indicated by horizontal lines on Figure 1, the stabilization system was unable to compensate for very high tether line tilt angles. The range of tilt angle compensation can be increased, however, by simply increasing the number of wraps of harness line around the control system pulleys. This will be done for future flights.

Motion-Sensing Platform

The performance of the Sky Platform can be improved in the future by tuning the automatic control loop's response to various tether line motions. The goal is to decrease the control system's sensitivity to high-frequency lateral accelerations while increasing its response to low-frequency angular accelerations that tilt the platform. A Motion-Sensing Platform has thus been developed to make the measurements required to design filters for the automatic control system on the Sky Platform.

An example of the performance of the MSP in measuring angular velocities is shown in Figure 2 by comparing the performance of the 9-accelerometer array on the MSP with that of a calibrated rate gyroscope (actually, a rate sensor assembly). MSP angular velocity values were obtained by integrating angular accelerations determined from

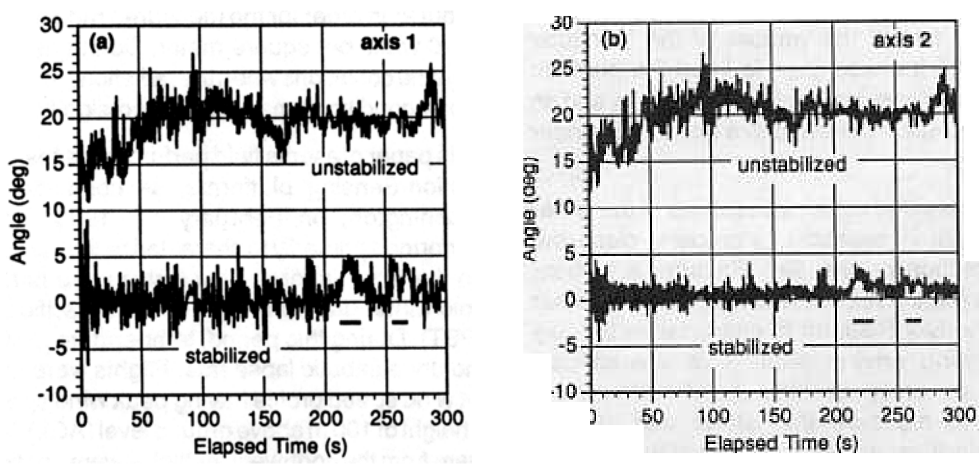

Figure 1. (a) Axis 1 and (b) axis 2 Sky Platform tilt angles for unstabilized and stabilized 5-minute ascents through depths of about 140 m AGL on February 17, 1993. See text for explanation of horizontal lines.

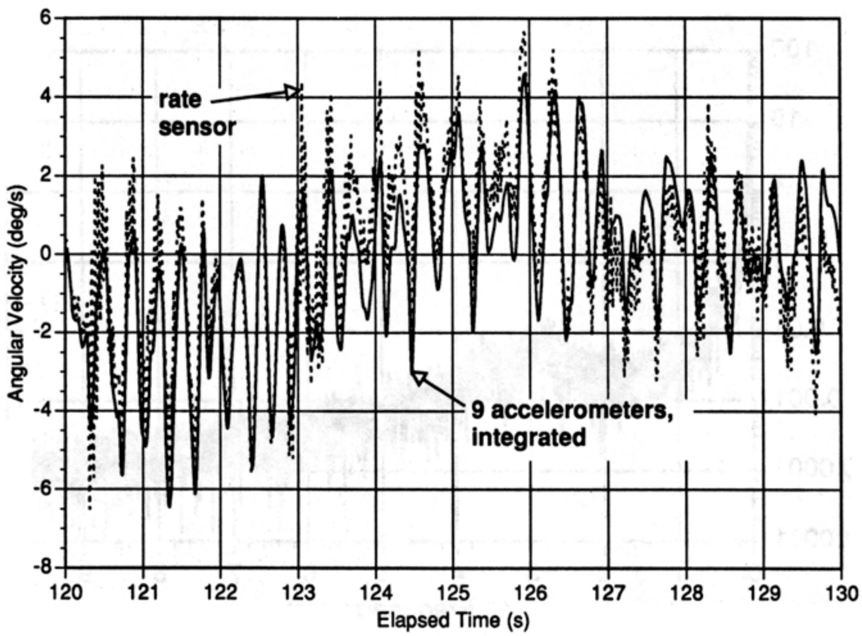

Figure 2. Angular rate measurements about the x axis of the Motion-Sensing Platform, as measured independently by a rate gyro and by an integration of angular accelerations determined with the MSP 9-accelerometer array. The 10-s time series corresponds to MSP ascent through the height range from 56 to 64 m AGL.

the 9-accelerometer array. A third-order Butterworth filter was used to pre-filter the angular acceleration data to reduce aliasing.

The conclusion from Figure 2 is that the MSP is able to measure angular accelerations reliably compared with the rate gyro for frequencies that are typical of the tether line. The amplitude spectrum of frequencies present on the tether line for the entire 5-min flight is shown in Figure 3, as obtained from the rate gyro. The spectrum shows a rapid falloff in the amplitude of tether line motions as frequency increases. A peak is apparent in the spectrum at 3 Hz. Other low-amplitude peaks (not shown) are present at 21 and 37 Hz, and efforts are under way to determine if these peaks are produced by the winch drive chain, vibrational modes of the platform frame, or other non-meteorological causes.

Conclusions

Initial tests of the prototype Sky Platform show that it is effectively stabilized to an average tilt angle of less than 1° with standard deviations of less than 2° under wintertime conditions with moderate shear in a 200-m-deep well-mixed boundary layer. The Motion-Sensing Platform appears to be capable of characterizing the dynamics of the balloon-Sky Platform-tether-line system and should be able to provide the information necessary to improve the control loop stabilization system on the Sky Platform. Further development of the Sky and Motion-Sensing platforms should result in a radiometric sounding system capable of measuring long- and short-wave irradiance and radiative flux divergence profiles in the atmospheric boundary layer;

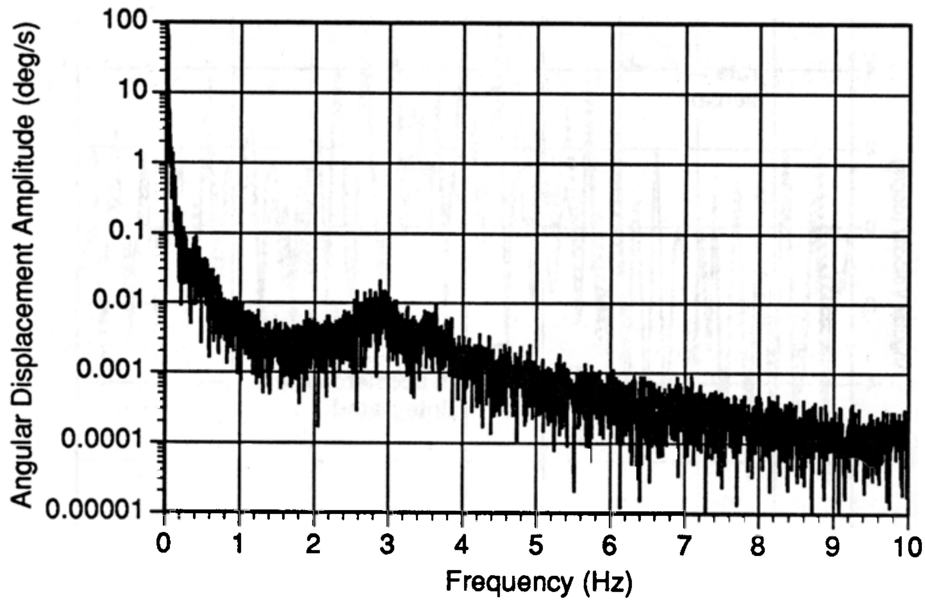

Figure 3. Spectrum of angular displacements measured by a rate gyro about the x axis of an unstabilized Motion-Sensing Platform during a complete 5-minute ascent through a depth of about 140 m.

the prescribed error bars will depend on radiometer calibration and Sky Platform stabilization performance.

Acknowledgments

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