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RESULTS FROM 1984 AIRBORNE DOPPLER LIDAR WIND MEASUREMENT PROGRAM: FLIGHT 6: ANALYSIS OF LINE-OF-SIGHT ELEVATION ANGLE ERRORS AND APPARENT DOPPLER VELOCITIES

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I. INTRODUCTION

Through analysis of ground return signals, a great deal of useful information can be obtained concerning the accuracy of the radial wind measurements made by the Marshall Space Flight Center (MSFC) Airborne Doppler Lidar System (ADLS) [1,2]. The purposes of this short study, which examines return signals obtained from the surface of the Earth during Flight 6, are to (1) estimate the errors in the fore and aft line-of-sight elevation (LOSE) angles, (2) determine the existence and magnitude of errors in the radial velocity measurements, and (3) better understand why ground returns frequently occurred within more than one adjacent range gate. During Flight 6, the ADLS made repeated passes over a portion of the California Central Valley that has a relatively uniform elevation near sea level, a characteristic particularly suited to the present purposes.

A detailed description of the ADLS can be found elsewhere [1,3]. Briefly, the ADLS emits discrete pulses of energy from a carbon dioxide laser and measures the Doppler-shifted radiation scattered back along the line of sight by naturally occurring aerosols. Since the aerosols are assumed to reliably follow the motion of the air, the results are measurements of the radial wind velocity. The receiver "listens" for a return signal at regular time intervals after a pulse is sent. A signal received within a certain time interval is equivalent to the same signal being received from a spatial interval, or range gate, along the line of sight at a certain distance from the lidar. The receiver listens at consecutive time intervals, thus a succession of range gates exists along the line of sight.

The information required to control the attitude of the lidar beam as well as to relate the measurements to Earth coordinates are provided by an inertial navigation system (INS). Since the observations are taken from a moving platform, the aircraft attitude and ground speed (provided by the INS) are taken into account in order to determine the "ground-relative" wind motion. Stated more simply, the actual wind motion is taken to be the difference between the Doppler-shifted signal and the aircraft motion. Theoretically, then, the measured radial velocity of returns from targets having no motion in an Earth coordinate system would be zero. In practice, the manner in which the apparent Doppler velocities of the ground depart from zero can provide information about the performance of the ADLS and the INS.

Prior to the first set of flights in 1981, a system was developed [4] for calibrating and pointing a germanium dual-wedge scanner which controls the attitude of the lider beam as it exits the side of the aircraft. The scanner was programmed to direct the beam within a horizontal plane, at angles of 20 deg fore and aft of an imaginary line perpendicular to the left side of the aircraft. Information from the aircraft INS was used to update the position of the scanner in response to changes in the aircraft pitch and roll. Subsequent data analysis showed that the data rate that information was available from the aircraft INS was not adequate to ensure that the pointing of the lidar beam was independent of aircraft attitude. Accordingly, an INS dedicated to the lidar system was mounted directly onto the optical table. In order to use the attitude information, a new control system was developed which allowed the scanner to respond more rapidly to the roll and pitch of the aircraft and, additionally, provided much more flexibility in beam pointing and increased system reliability. Up to 15 different scan angles, chosen from any plane within the 20 deg capability of the scanner, could be used in each scan pattern. The chosen angles remained fixed in space as long as the aircraft roll did not cause the scanner limits to be reached.

II. METHODOLOGY

During the flights the scanner was programmed to direct the beam into several planes, at least one of which was tilted below the horizon. This permitted the measurement of returns from ground, provided that the beam attenuation and slant range to ground were not too large.

Table 1 is a summary of the highlights of Flight 6. During the flight, different controlling parameters were entered into the inertial navigation system (INS) in order to minimize the LOSE angle errors noted on earlier flights by more accurately specifying the attitude of the scanner in response to roll and pitch information from the INS. At 202949 (all times are given in GMT) a new set of parameters was programmed into the INS and left in place until 213000, when the original parameters were restored. The latter change was made while scanning over the Central Valley.

As a visual aid to the interpretation of the signal amplitude and radial velocity measurements, software was written to display these data on the University of Wisconsin Man-Computer Interactive Data Access System (McIDAS) link at MSFC. False-color images showing amplitude and radial velocity within a scan plane were produced by specifying suitable time periods. Hard copies of the amplitude field were used to calculate the LOSE angle errors in the fore and aft scans. Signal returns from the ground appear as linear patterns of strong amplitude (e.g., see Fig. 2), at a slant range from the lidar that is dependent upon aircraft altitude and angle of inclination of the scan plane. Figure 1 is a schematic diagram of the scan geometry, where Z is the aircraft radar altitude, a and a' the computed and recorded LOSE angles, respectively, R the radial distance to ground, and $\Delta a = (a' - a)$ the error in the recorded LOSE angle; the computed LOSE angle is defined as $a = \sin^{-1}(Z/R)$. The radar altitude, obtained from the Airborne Digital Data Acquisition System (ADDAS) aircraft data tape, was used as well as United States Geological Survey (USGS) topographic maps that indicated the ground elevation in the vicinity of the aircraft to be approximately zero. In practice R was obtained from a McIDAS image and a' was taken directly from the flight data tape.

III. RESULTS

A. Estimation of LOSE Angle Errors

Figure 2, a gray-scale version of a McIDAS image showing the amplitude field for a' = -2.82 deg aft for the period 212500 to 213400, illustrates the abrupt change in R resulting from the entry of new parameters into the INS. The spurious data at the midpoint in the figure occurred as the parameters were being entered at ∿213000. Using this figure as well as one corresponding to forward scans, two sets of calculations were made, representative of the states of the INS before and after the parameters were entered. Table 2 summarizes calculations of LOSE angle errors for the fore and aft scans. Since the angle error is in the nature of an offset, these findings apply to the remaining scan angles as well. The results show that prior to 213000 the forward scans were made with negligible error, while the aft scans were low by approximately 1 deg. A consequence is that forward scans at a given angle are approximately collocated with aft scans at a recorded angle that is higher by approximately 1 deg. After 213000 the forward and aft a' are in error by 0.27 and -0.48 deg, respectively. Thus, the root-mean-square error decreased from 0.79 to 0.36 at the possible expense of requiring interpolation between scan planes to derive a two-dimensional wind field.

B. Estimation of Velocity Bias

1. Long-Term Variations. It is noted that the amplitude, velocity, and spectral width information recorded during the flights derive from integration of 20 laser shots at a time during the signal processing. For purposes of discussion, "long-term" refers to fluctuations over many shot integration periods, while "short-term" refers to fluctuations over the order of a few integration periods, or to a set of shots within one integration period. Analysis of 1981 flight data [5] revealed errors due to a Schuler resonance of the aircraft INS, which caused an erroneous component of the aircraft's ground-relative velocity vector to be subtracted from the lider-measured radial velocities. It was believed that these errors were as large as 4.5 m s^{-1} because of the lengthy time that the aircraft was in flight before collecting data. The Schuler resonance, found to have a period of 84 min, is an inherent source of error in an inertial navigation system. On the other hand, standard deviations and spectra of the velocity fluctuations measured by the lidar and independent instruments compared well. A conclusion from the analysis was that accelerations of the aircraft not detected by the INS could be accounted for by measuring ground returns following each horizontal observation and removing their apparent Doppler velocities in later analysis.

Figure 3 is a time series of apparent Doppler ground velocities for Flight 6 in its entirety. It is noted that, in addition to describing the pointing error of the lidar beam, these data provide an approximately continuous record of apparent Doppler velocities concurrent with the meteorologically significant clear air returns. Thus, it is possible to correct the radial wind measurements by taking into account the apparent Doppler velocities, in a manner to be discussed at the conclusion of this report. The data are organized into discrete groups, the gaps corresponding to heading changes (Table 1) that caused the scanner limits to be exceeded, or to temporary misalignment of the optical components due to body forces experienced during turns. The apparent velocities vary from approximately -1 to 2 m s^{-1}. Although the overall pattern is rather complicated, it is actually composed of segments in which the velocity varies linearly with time.

The apparent Doppler velocities do not indicate the presence of a Schuler resonance which, if present, would produce a sign change when the aircraft altered its heading by approximately 180 deg [5]. For example, at 2115 the heading changes by 170 deg, however, the apparent velocity changes from approximately 1.5 m s^{-1} to zero. At 2100, the heading changes by 30 deg, yet the velocity increases by approximately 1.0 m s^{-1}. While obvious errors are present in the INS, the cause is apparently unrelated to Schuler resonance. The apparent ground speed estimates generated by the dedicated INS for approximately 40 min after touch-down show slow fluctuations over the range 0.1 to 0.3 m s^{-1}, with no apparent periodicities, corroborating the lack of evidence of a Schuler resonance in the flight data.

2. Short-Term Variations. Portions of Figure 3 displayed using an expanded time scale show more subtle features and variations. Two expanded time series are shown in Figures 4 and 5. Figure 4 illustrates apparent velocities obtained over the California Central Valley at constant heading during the period 2117 to 2138. Figure 5 shows returns obtained in the direction of the Carquenez Strait at constant heading during the period 2236 to 2257. Both figures illustrate the overall linear behavior of the apparent velocity with time while the aircraft maintained a constant heading. Also evident in both figures, particularly Figure 4 (2217 to 2222), is a sinusoidal variation with amplitude of order 0.5 m s^{-1} and a period of approximately 1 min. This feature may be attributable to laser instability. Also present in both time series are fine-scale random fluctuations apparently related to the signal processing, as well as other, secondary errors not treated here.

Ground returns have also been obtained during operation of the Doppler lidar system in a ground-based configuration at MSFC. Figure 6 is a time series of apparent Doppler velocities obtained by directing the lidar at a mountain approximately 15 km away. With the exception of brief periods of laser moding, sinusoidal variations are present throughout the time series. Interestingly, the period of high-frequency sinusoid varies from approximately 30 to 60 sec, the amplitude varying from roughly zero to 0.3 m s^{-1}. The amplitude of the sinusoid appears to be modulated by a longer-period mode that is not well defined. Experiences with the ground-based Doppler lidar system have indicated that the amplitude and period of high-frequency oscillations can range from nonexistent to amplitude 1 m s^{-1} and period 60 sec, with the subtle presence of longer-period modes. These velocity variations are also attributed to laser instability.

C. Ground Returns in Adjacent Range Gates

Two characteristics of the ground returns warrant further attention before the apparent Doppler velocities may be subtracted arbitrarily from the clear air returns. First, as illustrated in Figure 2 the ground returns frequently extended over more than one adjacent range gate; second, R frequently varied by several range gates, an observation that apparently cannot be accounted for by topography. Three possible causes are identified which may have acted separately or in tandem.

1. Spurious Pulse Energy. Observation of the laser pulses prior to transmission through the scanner, as well as returns from hard targets during Flight 7, clearly showed "tails" before and after the main body of the pulse. Spurious energy outside the main pulse results, to varying degrees, in false returns from range gates in which there may have been insufficient backscatterers, i.e., a range ambiguity. Flight 7 data indicated that the degree of range ambiguity may depend in part on the slant range to the hard target and the amount of absorption of the beam by the intervening atmosphere, since spurious signals were associated with returns from an elevated target but not necessarily from the ground surface that was more distant by a factor of two. This explanation can also account for velocities in adjacent range gates not necessarily being equal. (The mathematics pertaining to an extreme form of this problem have been described in detail [6].)

2. Thin Dust Layer. A thin dust layer a few tens of meters thick immediately above the surface in an environment of vertical wind shear could yield returns in several adjacent range gates, including the ground, with differing radial velocities. This explanation is particularly appropriate in the Central Valley, where land usage is primarily agricultural. Horizontal and vertical inhomogeneities in the dust layer would influence the quantity and slant range of the apparent ground returns.

3. Delays in Scanner Response. A third explanation can be proposed that takes into account characteristics of the scanner mechanism and the software that drives it. During the flights the pulse repetition frequency (PRF) of the lidar was 110 Hz, and groups of 20 pulses were integrated to obtain single "radials" that were actually recorded. During the integration period of 0.182 sec the attitude of the scanner wedges is adjusted at a rate of 100 Hz, while roll and pitch information is being sent from the INS to the scanner at 20 Hz. There is a delay of up to 50 msec in the scanner response, thus the roll and pitch information is somewhat outdated by the time it is actually used. Although the wedge attitudes can be specified to within 0.01 deg, simulations [4] showed a scanner pointing accuracy of 0.1 deg. When taking together all of these factors, it becomes apparent that the attitude of the lidar beam may vary during the pulse integration period. Only minor changes in LOSE angle are required to produce significant changes in slant range (on the order of several hundred meters), particularly for shallow LOSE angles. For example, assume that during an integration period the LOSE angle varies by only 0.1 deg, comparable to the pointing accuracy. Using the four measured LOSE angles and the flight level from Table 2, the slant ranges would be increased by roughly 600, 300, 500, and 500 m, respectively. Furthermore, assuming a signal within a range gate is weighted in favor of returns from ground rather than aerosol, it would not be necessary for a ground return to be located very far within a range gate in order to make a significant contribution. Thus, returns from the ground could appear in several adjacent range gates as the slant range varied during the integration period.

IV. CONCLUSIONS

1. This study has identified errors in the recorded LOSE angles. Using images made of amplitude fields, estimates were made of the true LOSE angles. A time dependence was found that relates to the use of different parameters with the INS to control the attitude of the lidar beam. During the first part of the flight, a relatively close correspondence existed between forward scans, and aft scans with recorded LOSE angle 1 deg higher. Later, fore and aft scan planes were different by a significant fraction of a degree, suggesting the need for an interpolation scheme to derive two-dimensional wind fields.

2. No evidence was found of a Schuler resonance phenomenon noted during the 1981 flights. However, significant errors were found with the INS. Apparent velocities of the ground were as large as 2 m s^{-1}, much less than those noted for the 1981 flights. During flight segments in which a constant heading was maintained, the apparent velocities varied linearly with time. Superimposed on the linear trend were sinusoidal and random components, the former having a period and amplitude of approximately 1 min and 0.5 m s^{-1}, respectively.

3. Returns apparently associated with ground extend over several range gates, an observation not readily explained by the relatively flat topography. Three possible explanations were proposed. First, when taking the lidar pointing accuracy together with the delays in the scanner response, the lidar beam elevation may have

varied significantly during the time interval when the pulses were integrated. Using findings from the LOSE angle error analysis and information about the ADLS, it was shown that an angle deviation only of the order of the pointing accuracy could explain this feature. Other possibilities include range ambiguity due to pre- and post-pulse energy tails, and the presence of a thin, inhomogeneous dust layer in an environment of vertical wind shear.

4. In light of the linear dependence of the apparent Doppler velocities as a function of time, an initial approach to error reduction would be to subtract from the clear air velocity data a linear least-squares fit to the apparent velocities for each flight segment with constant heading. A somewhat more accurate approach would be to apply a smoothing operator to the apparent velocities prior to subtraction, thus more completely eliminating the sinusoidal component. Either of these approaches would undoubtedly have a significant impact on the resulting wind field. The magnitude of the errors cited in this study represent a significant fraction of the clear air radial velocities, which had a magnitude of 5 ms^{-1} or less over the California Central Valley.

5. The addition of the dedicated INS and the more flexible scanner control system has increased the effective accuracy of the measurements. The INS errors are approximately half of those reported for the 1981 flights. More importantly, the existence of an approximately continuous time series of apparent Doppler velocities provides the means to eliminate these errors almost completely.

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TABLE 1. SUMMARY OF FLIGHT 6 SEGMENTS WITH CONSTANT HEADING

Time (GMT) Start	Stop	Run	Avg Pres	Alt(m) Rad	Hdg (dg)	Gspd (m)	Comments
201446							Take-off
202949							New pitch and roll offsets installed on INS
204840							Begin data acquisition; LOSE 0, -1, -3 deg fore and aft
204840	205945	1	724	790	320	113	Carquenez Strait
210015	210405	1	877	939	350	113	Carquenez Strait
210445	211525	1	739	776	350	111	Carquenez Strait
211645	214015	2	730	800	160	108	California Central Valley
213000							Original pitch and roll offsets installed on INS
214330	215145	4	739	800	330	111	Carquenez Strait; LOSE 1, 0, -1, -2, -3 deg fore and aft
215235	220645	4	747	777	350	111	Carquenez Strait
220915	223210	5	738	799	160	106	California Central Valley
223605	224655	6	736	789	330	113	Carquenez Strait
224845	225715	6	732	758	350	113	Carquenez Strait
230035	232215	7	729	785	160	113	California Central Valley
232515	233815	8	727	777	330	119	Carquenez Strait
235711							Touch-down

TABLE 2. SUMMARY OF CALCULATIONS TO DETERMINE ERROR IN LINE-OF-SIGHT ELEVATION (LOSE) ANGLE, DENOTED BY a.

R is the slant range from aircraft to ground, Z the aircraft radar altitude, a the computed LOSE angle, and a = a' - a, where a' is the recorded LOSE angle.

TIME	< 213000		> 213000	
DIRECTION	FORE	AFT	FORE	AFT
R (m)	16200	11600	18100	14000
Z (m)	797	797	805	805
a (deg)	2.82	3.94	2.55	3.25
a (deg)	0.00	-1.12	0.27	-0.43
rms err (deg)	0.79		0.36	

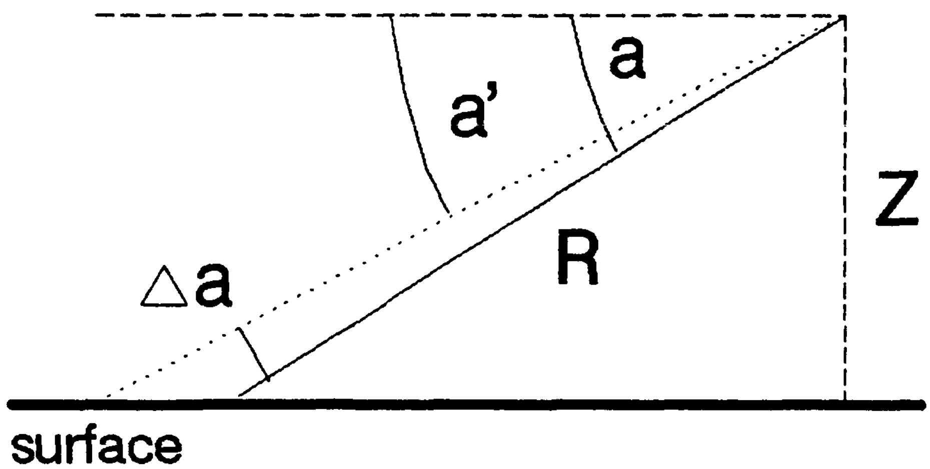

Figure 1. Simplified vertical cross-section of Airborne Doppler Lidar System scan geometry during 1984 flights. Z is aircraft radar altitude, a and a' the computed and recorded LOSE angles, respectively, R the slant range to ground, and Δa (= a' - a) the error in recorded LOSE angle.

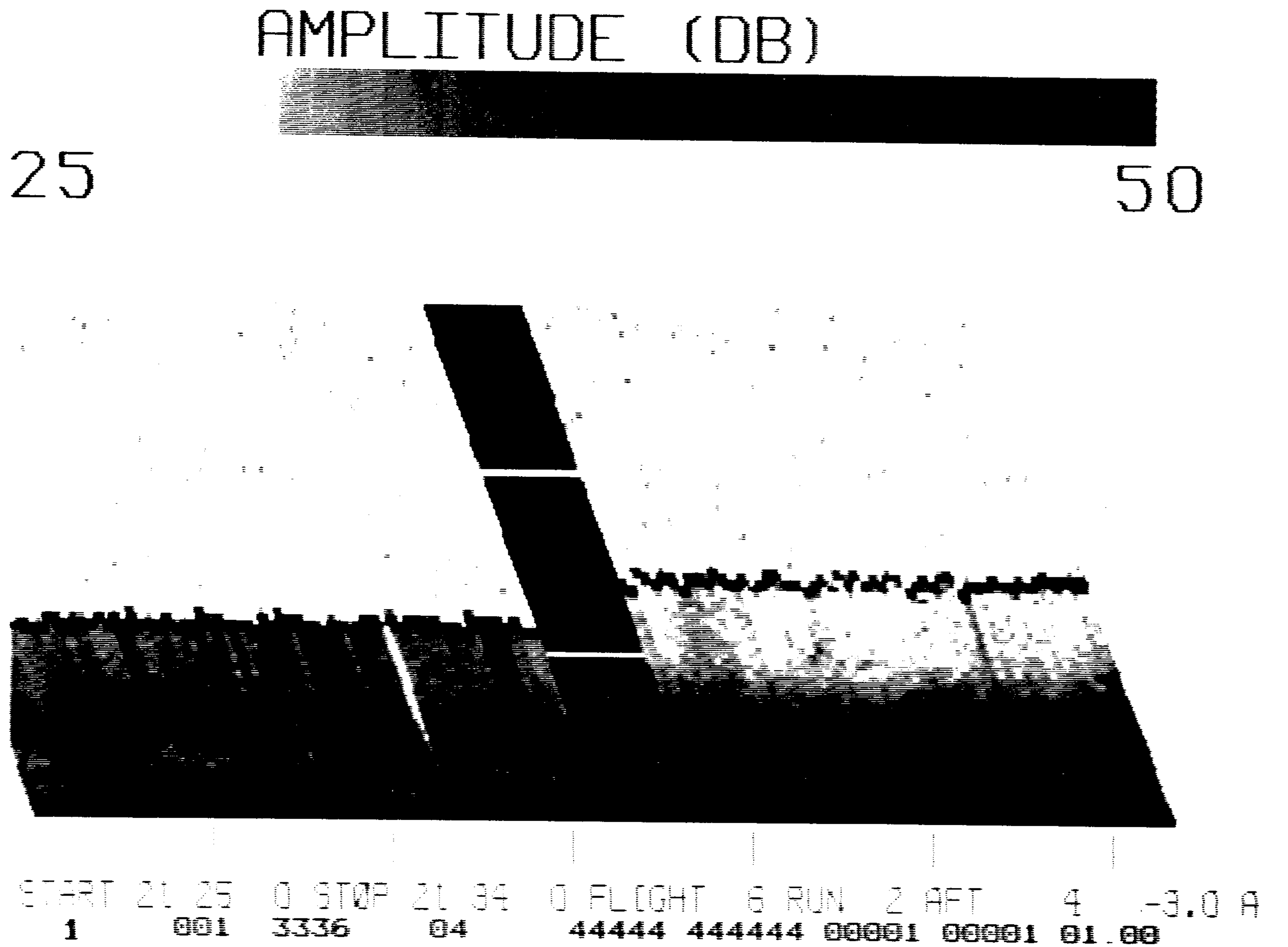

Figure 2. McIDAS image of signal amplitude field measured in aft direction, a' = -2.82 deg, for period 212500 to 213400 GMT. Gray-scale shows amplitude variation from 25 to 50 dB. Tic marks at bottom of figure denote 10 km intervals. Figure shows abrupt change in slant range R to ground due to entry of new controlling parameters into inertial navigation system.

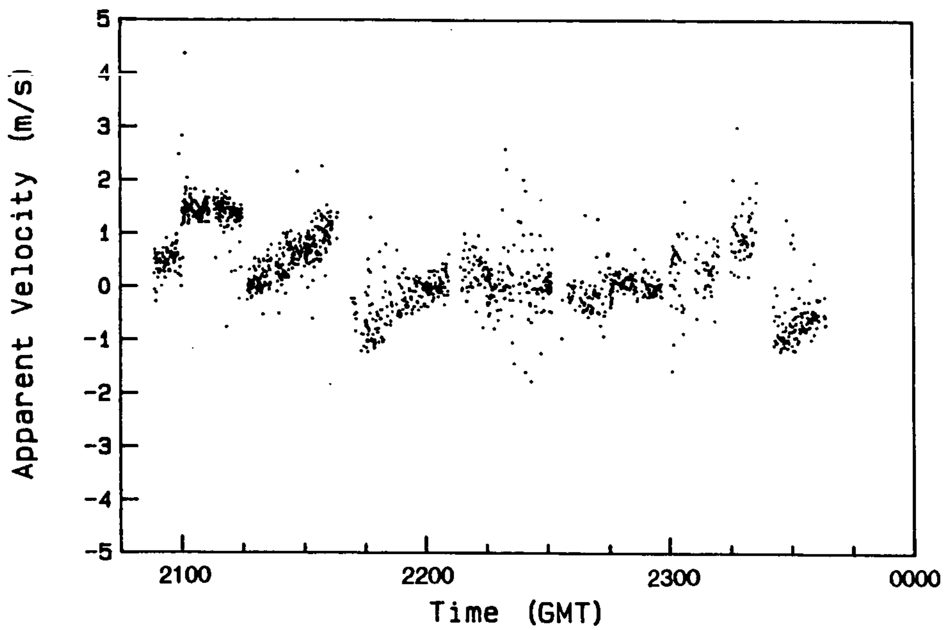

Figure 3. Time series of apparent Doppler ground velocities for Flight 6 in its entirety.

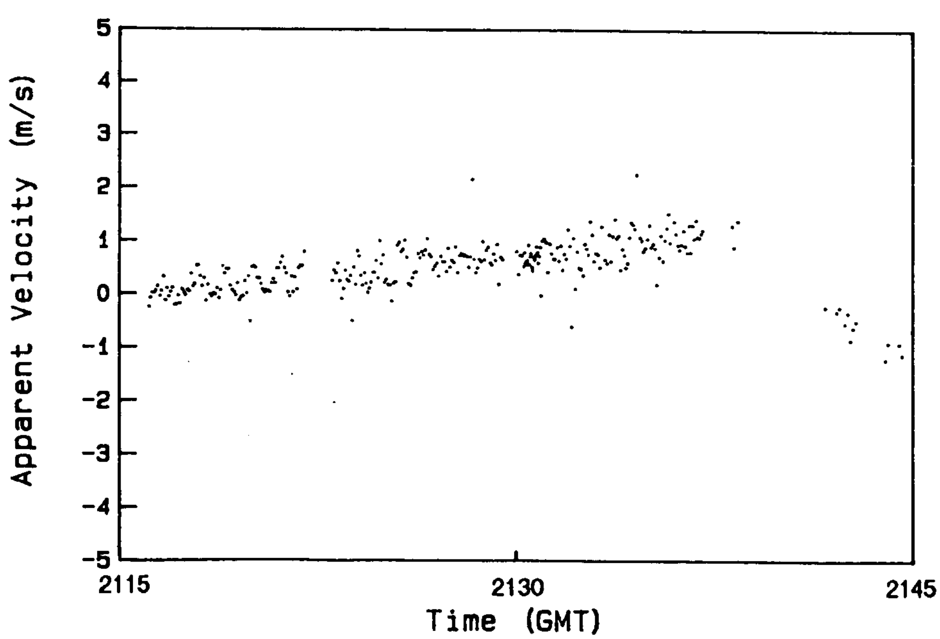

Figure 4. Time series of apparent Doppler ground velocities measured in aft direction for a' = -2.82 deg. Note time period 2117 to 2138 GMT, corresponding to heading of 160 deg. High-frequency oscillations, particularly evident during 2117 to 2122, are indicative of laser instability.

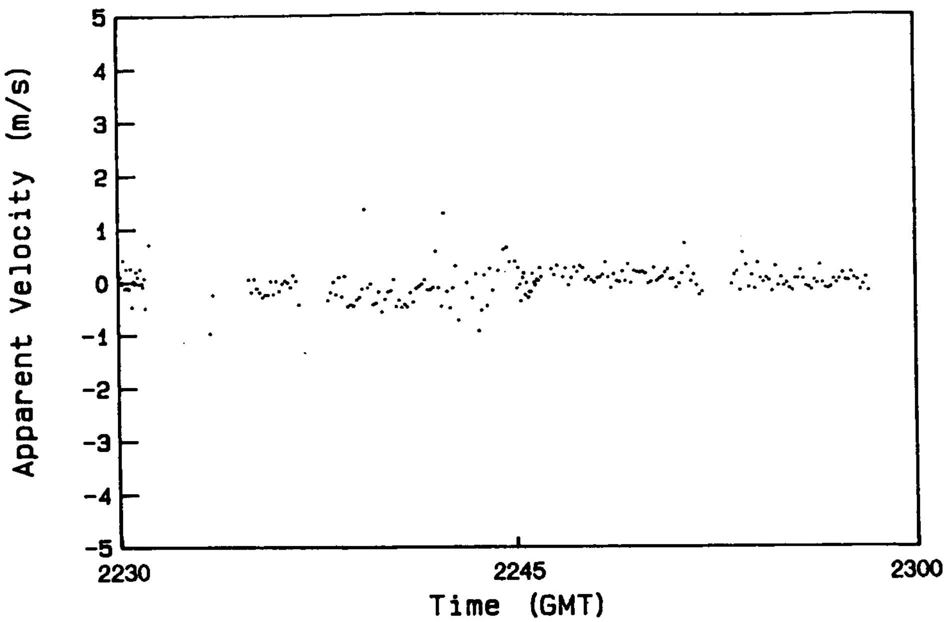

Figure 5. Same as Figure 3, except note time period 2237 to 2257 GMT, corresponding to heading of 330 deg.

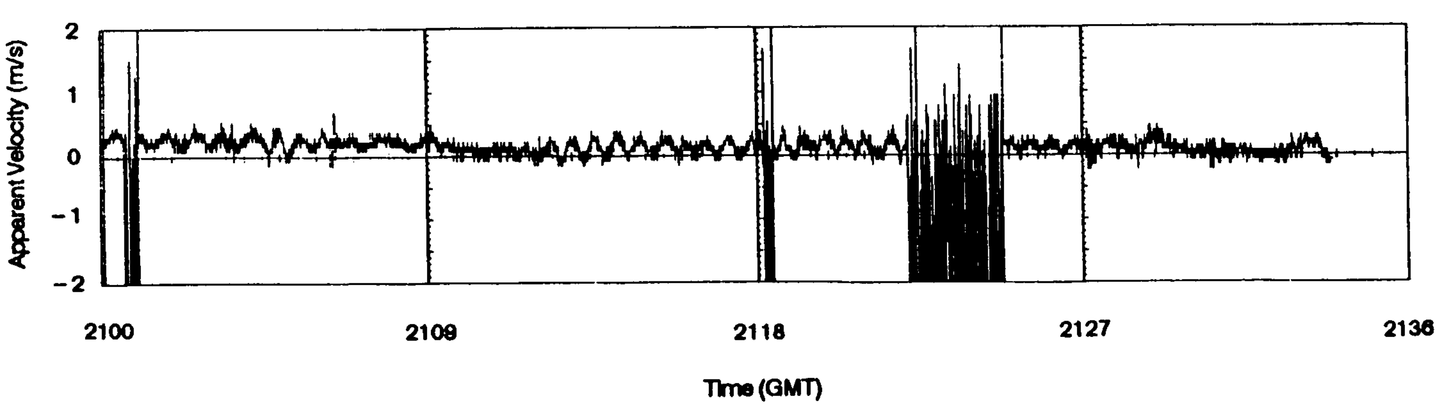

Figure 6. Time series of apparent Doppler velocities obtained at the Marshall Space Flight Center on 6 May 1983. Lidar was directed at a mountain approximately 15 km distant. Time series shows high-frequency oscillations, similar to those in Figures 4 and 5, whose amplitudes appear to be modulated by a lower-frequency mode that is superimposed.

APPROVAL

RESULTS FROM 1984 AIRBORNE DOPPLER LIDAR WIND MEASUREMENT PROGRAM

Flight 6: Analysis of Line-of-Sight Elevation Angle Errors and Apparent Doppler Velocities

By Jeffry Rothermel

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

G. F. McDONOUGH
Director, Structures and Dynamics Laboratory

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16. ABSTRACT

During the summer of 1984 the Marshall Space Flight Center's Airborne Doppler Lidar System (ADLS) made a series of wind measurements in the California Central Valley. This study quantifies the lidar beam angle errors and velocity errors through analysis of ground return signals. Line-of-sight elevation (LOSE) angle errors are under 1 deg. Apparent Doppler ground velocities, as large as 2 m s^{-1}, are considerably less than in a previous flight experiment in 1981. No evidence was found of a Schuler resonance phenomenon common to inertial navigation systems (INS), however the aperiodic nature of the apparent velocities implies an error in the INS-derived ground speeds. Certain features and subtleties in the ground returns are explained in terms of atmospheric structure and characteristics of the ADLS hardware and software. Finally, least squares and low-pass filtering techniques are suggested for eliminating errors during post-processing.

17. KEY WORDS
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