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STUDY OF
SOFTWARE APPLICATION OF AIRBORNE LASER DOPPLER SYSTEM FOR SEVERE STORMS MEASUREMENT

FINAL REPORT

April 9, 1979

Prepared for:

The National Aeronautics and Space
  Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

M&S COMPUTING, INC.

PREFACE

This report describes the significant considerations for performing a Severe Storms Measurement program in real time. Particular emphasis is placed on the sizing and timing requirements for a minicomputer-based system. Analyses of several factors which could impact the effectiveness of the system are presented. This study was performed by M&S Computing, Inc., for the Marshall Space Flight Center, Alabama, under Contract No. NAS8-33089.

Prepared by:

P. L. Alley
H. B. Jeffreys

Approved by:

W. E. Salter
Dr. W. E. Salter
Manager, Systems Engineering

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LIST OF ACRONYMS

ADDAS	Airborne Digital Data Acquisition System
CAT	Clear Air Turbulance System
DMA	Direct Memory Access
DPS	Data Processing System
INS	Inertial Navigation System
MOPA	Master Oscillator - Power Amplifier
PRF	Pulse Repetition Frequency
SSMS	Severe Storm Measurement System

LIST OF FIGURES

1. INTRODUCTION

The use of Doppler lidar systems has been shown to be an effective means for studying (measuring) atmospheric phenomena such as aircraft wake vortices, dust devils, and gust fronts associated with approaching thunderstorms. These systems employed continuous wave (CW) and, later, pulsed lasers as the measurement devices, feeding either translated (offset) or untranslated (no offset) velocity data in the CW system, or raw integrated spectral data in the pulsed system, to a data collection and analysis device. For both systems, this device was a Digital Equipment Corporation (DEC) minicomputer PDP-11/35. Continuation of the study of atmospheric phenomena, particularly clear air turbulance (CAT), has led to recent fielding of the pulsed lidar aboard a research aircraft (CV-990) at Ames Research Center, California. Previous CAT missions with a similar system were performed in 1973; however, no real-time data analysis and display mechanism was included in the deployment. Although detailed analysis of data taken during the current flight series has not been completed, the system's performance has been promising enough to project a natural extension of the single dimension velocity measurement system currently in use to the measurement of two-dimensional flow fields in a horizontal plane.

A detailed examination of the hardware requirements for a two-dimensional flow field measurement system was performed in 1977 by the Raytheon Company (1). The results of the study indicated that, indeed, such a system was feasible utilizing much of the existing CAT lidar hardware. Additionally, a preliminary examination of a possible data processing system was performed in the study. A more detailed examination of the software and data handling hardware requirements for performing real-time data acquisition, data analysis, and data display is required to adequately size the computer solution to two-dimensional flow field analysis.

1.1 Scope

Initially the study effort was to be constrained to an analysis of the data processing and data storage requirements for flow field analysis as described in the hardware study performed by the Raytheon Company under NASA Contract NAS8-31721. Refinements in the configuration of the hardware and, in particular, definition of the signal processor functions have expanded the scope to include error analyses of the effects of pulse integration and moment estimation. Additionally, alternative means of data processing given certain additional items of information regarding the input data were examined. The analyses presented herein encompass the problems of data acquisition, data storage, data registration, correlation, and flow field computation, and error induced by aircraft motion, moment estimation, and pulse integration.

1.2 Outline of Study

The analysis of two-dimensional flow field computations was approached by first examining the base configuration of the hardware as presented in the Raytheon report. A thorough understanding of the geometry of the measurements, the interfaces and data rates involved in acquiring the data was required before a detailed examination of the algorithms necessary for data registration and correlation could be attempted. Elements of the review will be found in Section 2 and in each of the sections described briefly below. Basically each section is divided into two discussions: the first discussion examines the base configuration with respect to the subject under analysis; the second discussion details the latest (recommended) approach, taking into consideration the developments and refinements in the hardware definitions and interfaces.

The analysis of data acquisition from the lidar and a definition of the apparent timing for the base system and for the current recommended approach is provided in Section 3. Consideration of the various interfaces required for data acquisition is provided to support the sizing and timing estimates.

Section 4 describes the data storage requirements. Consideration is given to the data storage requirements for raw data from the lidar and for a portion of the calculated parameters. Special emphasis is placed on determining a data organization which will be most efficient in terms of memory allocation and will accommodate certain algorithmic requirements.

Section 5 provides a discussion and examination of the data processing requirements for the Severe Storm Measurement System. A detailed examination of the geometry of the problem is beyond the scope of this study; however, sufficient analysis is presented to clarify the discussion. The emphasis in Section 5 is focused on the methods of data registration, data correlation, and two-dimensional flow field analysis. Several references to the inputs received from an interface microprocessor appear in the discussion. It is assumed that, while the precise function of the microprocessor and its interfaces to the other elements of the Severe Storms Measurement System have yet to be defined, treating this interface in "black box" fashion will both show the feasibility of its employment and serve as a recommendation for this approach toward satisfying system requirements.

Analyses of several factors which could significantly impact the approach to data processing are presented in Section 6. Several parameters are scrutinized for the possibility of inducing errors into the data and include such items as aircraft motion during the scan, uncertainties induced by the resolution and accuracy of the Inertial Navigation System (INS), velocity computation using moment estimation and integration, and lidar scanner beam pointing errors resulting from the accuracy of aircraft attitude corrections.

Section 7 provides a review of the major conclusions arising from the study and includes preliminary recommendations for system data processing and storage design and definition/recommendations for further study efforts and data processing simulation.

2. BASE CONFIGURATION

This section contains a brief description of the basic pulsed laser Doppler system configuration which is outlined, in detail, in the Raytheon final report under NASA Contract NAS8-31721. The system described therein was designed through consideration of the physical characteristics of the phenomenon to be measured, the severe storm, and an understanding of the state of the art in laser Doppler systems and data processing hardware. The report contains sections that outline the storm characteristics with discussions of the velocities to be measured, the parameters to be measured/recorded, the system configuration and performance specifications, and the hardware requirements for accomplishing the measurement program. The basic configuration of the Severe Storm Measurement System (SSMS) consists of four major subsystem elements: the laser, the scanner, the processor, and the data analysis system, all located in a Convair 990 type aircraft.

The basic system requirements, as outlined in the Raytheon report, were also compared to the capabilities of the existing Clean Air Turbulence Measurement System.

This section is divided into five subsections which describe the aircraft and the four major subsystem elements of the SSMS.

2.1 The Aircraft

The aircraft considered in the base configuration is a Convair 990 which accommodates the SSMS in a way similar to that of the Clean Air Turbulence System (CAT). It was assumed that access to a 14-inch by 14-inch aircraft window would be possible and that the desired field of view could be acquired without interference from the window, wings, engines, or tail sections.

The aircraft is assumed to be capable of flying at speeds between 100 m/sec and 250 m/sec and providing and maintaining pitch, roll, yaw to the tolerance specified in Table 3-1 of the referenced Raytheon report (1).

The Inertial Navigation System (INS) of the aircraft is assumed to provide aircraft position to an accuracy of 0.5 to 1.0 nautical mile for up to an hour (drift rate 0.5 to 1.0 nautical mile per hour).

2.2 The Scanner

The scanner configuration described in the referenced report (1) is designed to accomplish the spatial coverage requirements of the storm, using the motion of the aircraft to cover the required area. The scan concept was determined by the required angular coverage as viewed from the aircraft. The most important coverage region was considered to be the horizontal plane. The requirement to measure the velocity vector in the horizontal plane requires the scanner to make at least two independent observations at each point of interest, with a sufficient angle between them so that the velocity components may be adequately resolved. It is also assumed necessary to make the two observations during a sufficiently short time interval, such that no change in the vector velocity at the point in question occurs.

The scanner described in the referenced document (1) accommodated a scan pattern which repeats itself with a period of 0.5 to 1.5 seconds for an aircraft moving at 200 m/sec. A potential scan pattern is shown in Figure 2-1 where the scanner looks forward of the normal to the flight path for a short period of time and then changes to a line-of-sight looking to the rear of this plane for an equal length of time.

The physical configuration of the scanner is such that no unusual shapes or large holes on the exterior of the aircraft will exist. The scanner configuration is such that it can accommodate stabilization requirements of the scanner in the event aircraft flight stability is intolerable. (From Table 3-1 of referenced report (1).)

Two potential designs that were considered for the base configuration scanner are given in Figure 4-5 and Figure 4-6 of the referenced document (1). The scan angles for the scanner are ±30 degrees about the normal aircraft flight path and provide a 60 degree angle between the two looks of a velocity flow field point. The scanner switching time is considered to be 0.25 seconds. This is the time required for the scan mirror to go from 30 degrees aft to 30 degrees forward looking or vice versa.

A more detailed description of the base configuration scanner design is given in Section 4.3 of the referenced document(1).

2.3 The Processor

The digital data processor in the basic configuration was assumed to be able to accept all PRF's and pulse widths associated with the present CAT and the TEA transmitter. It is also assumed to have the capability to handle variable pulse integration from a single pulse to at least 0.5 second. The integration is controlled by both a selector switch and by

SCAN CONCEPT

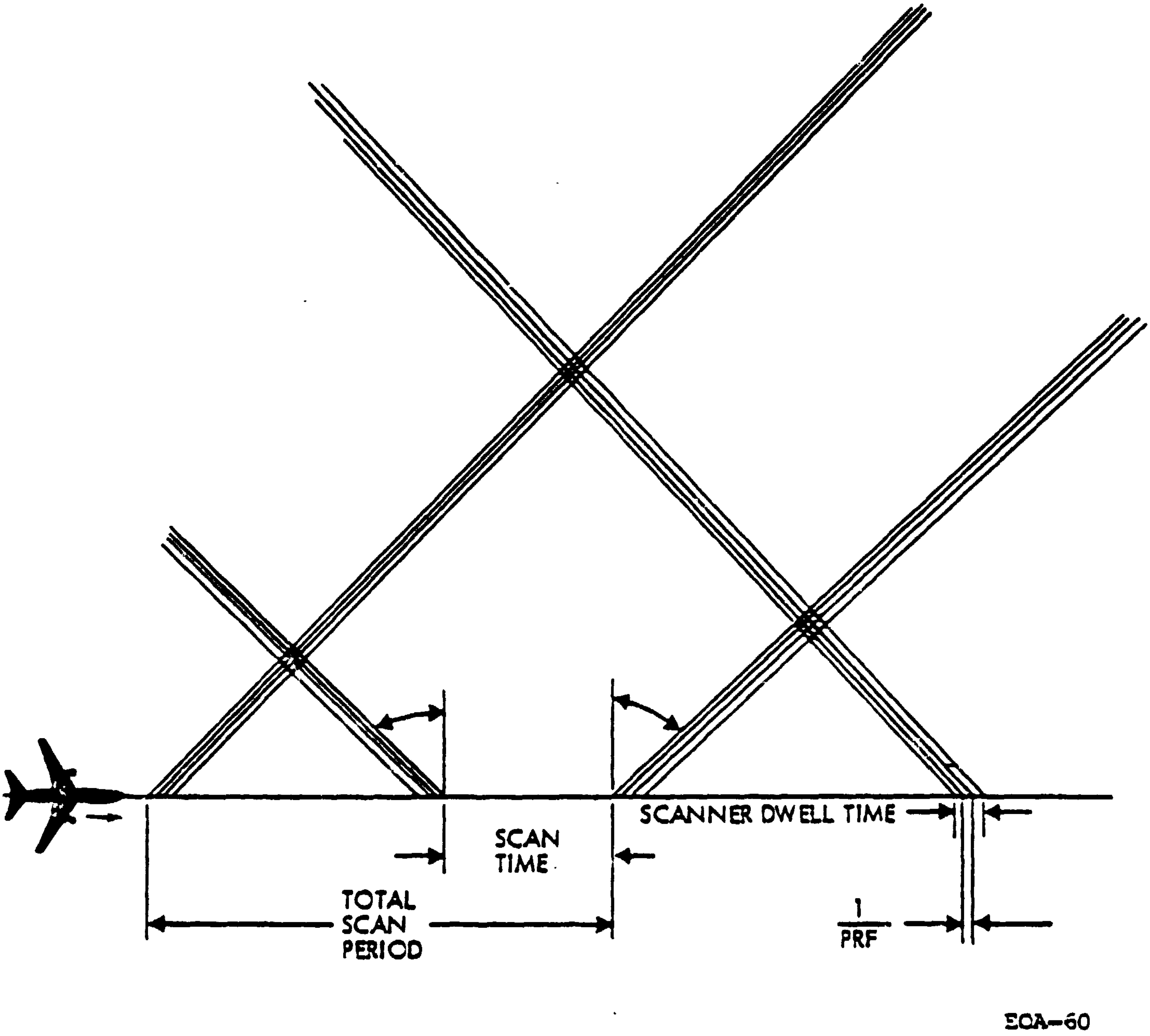


Figure 2-1

the computer (data processing system). The spectrum outputs are available for recording and display and the moments of the spectra are calculated for use in the data processing system. An interface is provided for the moment and aircraft data to be input into the computer and for the offset frequency and start/stop integration commands to be output from the computer.

The signal processor configuration is presented in block diagram form in Figure 2-2. The details of the base configuration digital data processor are contained in Section 4.4 of the referenced Raytheon final report (1).

2.4 The Laser

The base configuration laser is assumed to be a modification of the CAT system laser and will operate reliably in the aircraft and turbulant environment. The CAT system and laser as it presently exists would not be suitable for performing the two-dimensional velocity measurements of the severe storm.

The base configuration assumes a laser system that is capable of delivering sufficient energy with a one microsecond pulse at a 200 Hz pulse repetition frequency with coherency to permit Doppler data to be collected to a range of 10 km in the vicinity of a severe storm.

The laser system may be a modified Master Oscillator - Power Amplifier (MOPA) or a TEA laser design. A more complete discussion of the potential base configuration is presented in Section 4.6 of the referenced Raytheon final report (1).

2.5 The Data Processing System

The basic data processing system configuration is assumed to reduce the velocity data (along various lines of sight), the aircraft position orientation data, and the storm movement/location data (as provided by radar) to a two-dimensional velocity flow field in a coordinate system referenced to some initial location of the storm. It is assumed desirable to perform as much of the data processing as possible in real time.

It is assumed that this data processing can be performed using a PDP-11/35 type computer with some supporting computer hardware, data displays, and recorders.

The base data processing system performs a number of functions. First, it calculates the velocities from the three moments available from the processor and stores them in appropriate locations, along with the supplementary data

SIGNAL PROCESSOR BLOCK DIAGRAM

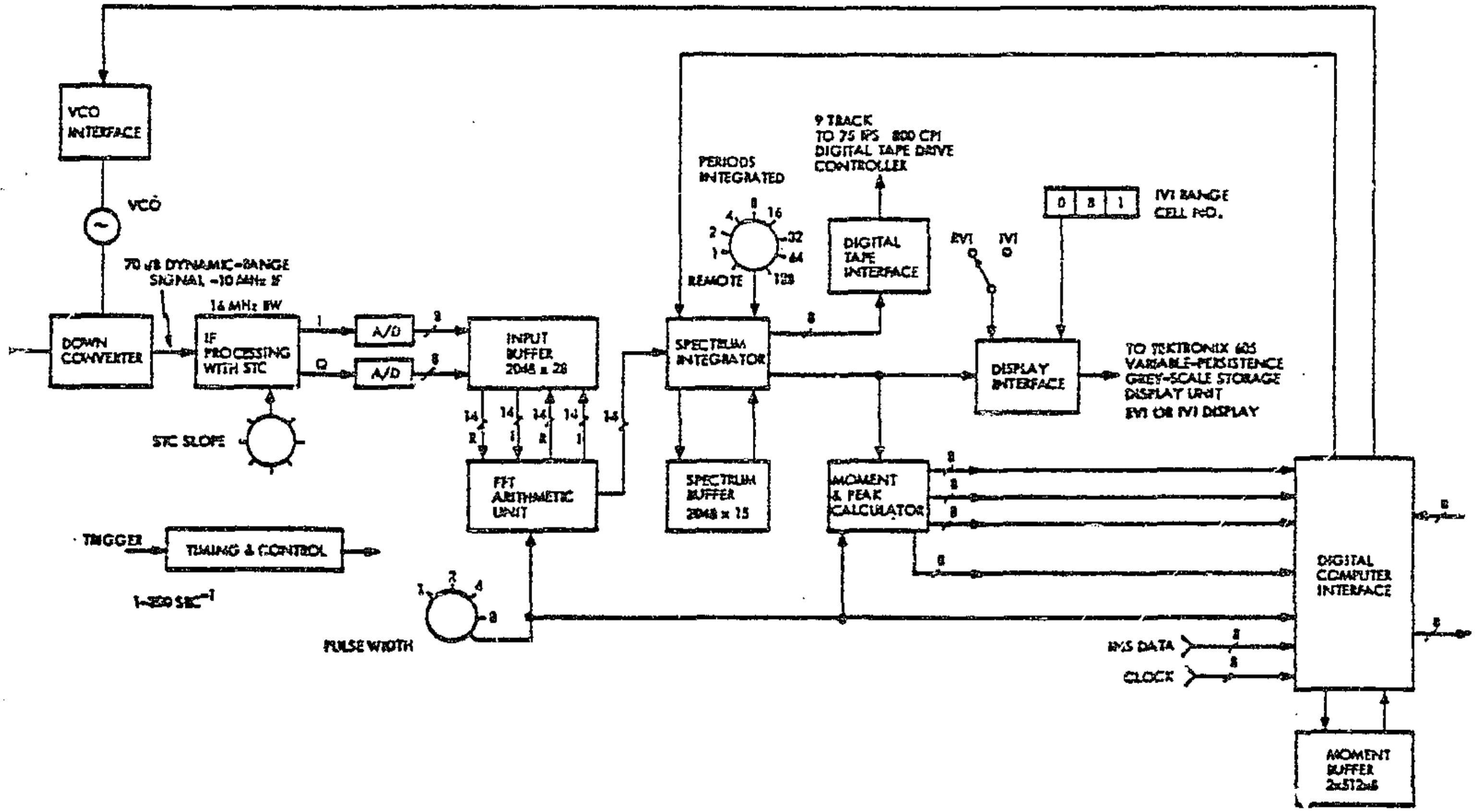


Figure 2-2

required to perform the registration of data points. The next step locates the position and orientation of the aircraft at the time of data collection, references it to the initial position of the storm, and stores the necessary information for later use. The base configuration assumed that to generate the velocity field, it is necessary to find the coordinates of each point at which a forward and backward looking scan cross, and to identify the correct range bin along each line-of-sight such that the appropriate line-of-sight velocity data is obtained. Then it is necessary to resolve these velocity components in the desired coordinate system and display them in a suitable format. It is assumed desirable to save the processed and unprocessed data for further analysis in a postprocessing mode.

A more complete description of the base configuration for the data processing system is given in Section 4.5 of the referenced Raytheon final report (1).

3. DATA ACQUISITION

The problem of acquiring the appropriate data for the analysis of two-dimensional flow fields involves several questions; namely, what data are required to perform the algorithmic functions, how quickly can the data be obtained, and, from what sources will the data be required. By examining the problem from the computations required to perform the flow field analysis, one can define certain obvious items of data that must be obtained. Included in this category are, of course, spectral data from the lidar signal processor, aircraft position, angle of scan, and aircraft heading. Certain other pieces of information are required; however, most are derived from the data identified above and do not represent additional interface considerations. The acquisition of this data would require two, possibly three, independent interfaces between the host computer and the supplying devices. Reduction of the number of interfaces required to obtain the requisite data has a direct impact on the time available for flow field computations.

3.1 Multiple Interfaces

The configuration described in the base report is presented in simplified form in Figure 3-1. The interface to the Airborne Digital Data Acquisition System (ADDAS) is shown simply as INS (Inertial Navigation System). The data to be acquired via this interface would be requested upon receipt of the spectral data resulting from each pulse transmitted during the time-on-target integration period. The number of integrations is variable and, for this discussion, would be performed by the host computer. The time between pulses is a function of pulse repetition frequency (PRF). A PRF of 140 then yields an interpulse period of approximately seven milliseconds (refer to Figure 3-2). Assuming an integration cycle of 25 pulses, the scanner would have a time-on-target of approximately 178 milliseconds in each of its pointing directions. The time required to reposition the beam between integration cycles is taken to be 250 milliseconds. Each transmitted pulse has a useful data period of less than a millisecond, leaving nearly the full interpulse period available for signal processing, data formatting, and data transfer to the host computer. If one assumes that the signal processing and data formatting functions take only the remainder of the one millisecond used as a base for useful data periods per pulse, one can now examine the transfer functions between the signal processor and the computer, and the request for (and receipt of) aircraft data from the ADDAS system.

First, it is necessary to examine the current mode of interfacing with the signal processor, e.g., handshake at a defined rate of transfer. Once the received lidar signal has been processed

SIMPLIFIED INTERFACE CONFIGURATION OF THE BASE SYSTEM

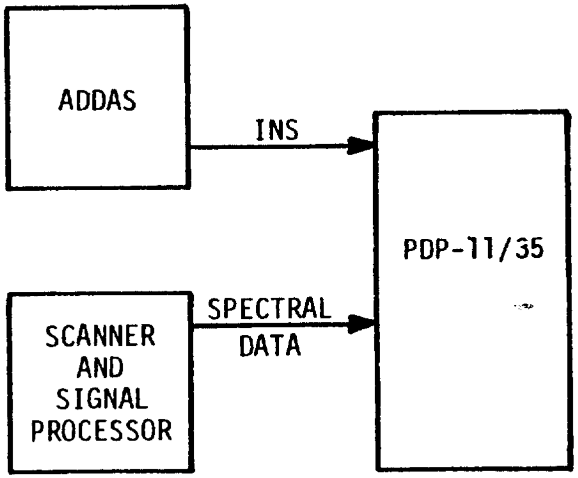


Figure 3-1

TIMING OF INTERFACE WITH PDP PERFORMING PULSE INTEGRATION (25 PULSES)

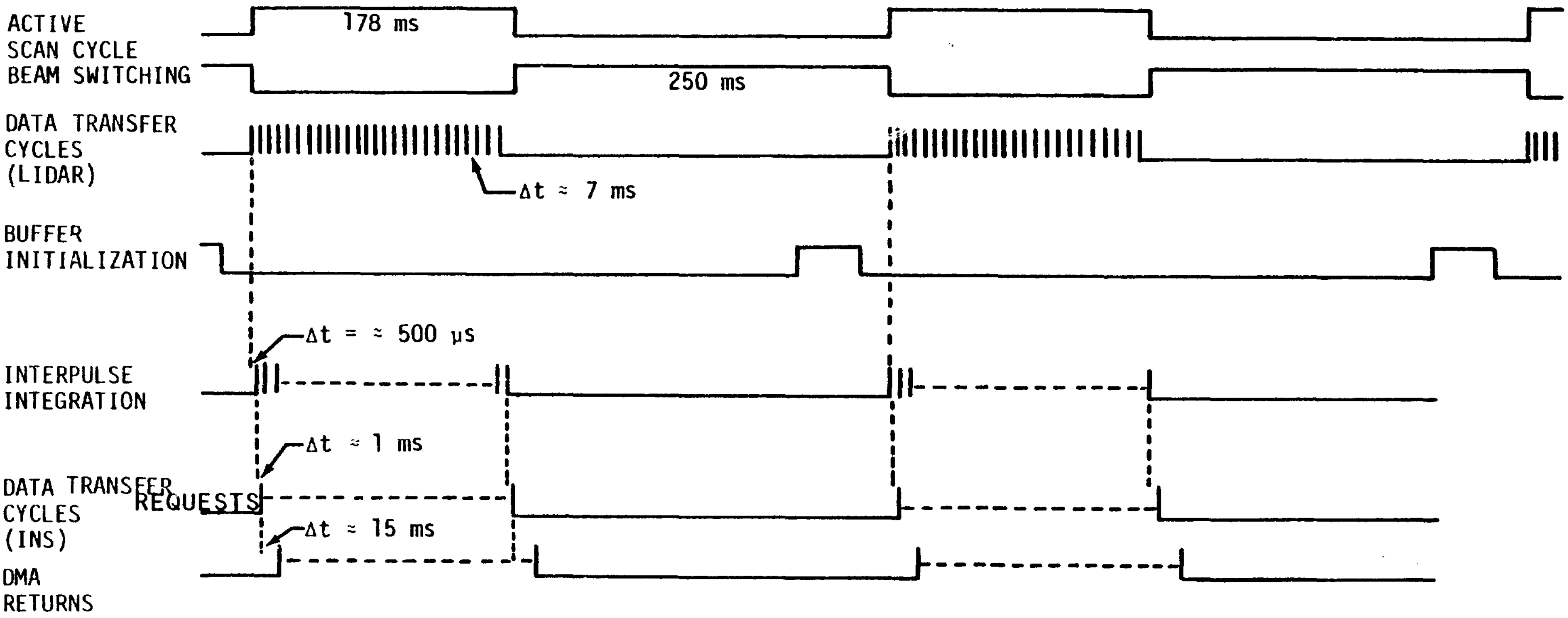


Figure 3-2

and formatted, data is placed on the interface and clocked to the PDP-11/35 every 250 milliseconds. For the 192 possible words of spectral data, this transfer would require 48 milliseconds to complete. Considering an interpulse period of seven milliseconds, an alternative method must be found.

Direct Memory Access (DMA) interfacing between the signal processor and the PDP-11/35 would significantly reduce the time required for lidar data transfers. Since DMA devices correspond directly with no processor resources required, the transfers occur essentially at memory speeds, in this case, every microsecond. The total transfer, then, could be completed in less time than a single transfer under the current scheme.

The aircraft positional information is also required for every pulse in order to perform centroiding calculations for each beam position. Upon receipt of the DMA completion flag, a request would be made of ADDAS to supply the current set of aircraft data. Currently, this procedure requires at least 15 milliseconds. Even with employment of a DMA interface to ADDAS, the bulk of the time is spent in obtaining and formatting a buffer for output. Here again, the intervals for obtaining the requisite data are too long to be useful since the PDP would be strained to maintain sufficient buffers over several pulses. Additionally, so much of the processor resources would be tied up performing pulse data integration that the remaining time, less than 250 milliseconds, would be insufficient to perform the flow field computations.

3.2 Single Interface

To alleviate the burden of integration and multiple interfaces, pulse data integration should be performed by the lidar signal processor and a single interface established such that the maximum amount of time is available for on-line data processing. The addition of a microprocessor which could perform some of the requisite computations, accept the spectral data from the signal processor and scan position data from the scanner, and format a single buffer for DMA transfers at the completion of each integration period would greatly reduce the load on the PDP-11/35 and extend the time available for real-time processing of the flow field data. Figure 3-3 presents the timing associated with such an interface under the same set of assumptions presented earlier. The effective computation time between successive aft scans is nearly four times that which would be available otherwise. The configuration of the hardware interfaces is presented in Figure 3-4. Although the precise interface signals are not yet fully defined, the configuration suggests the feasibility of such an interface device.

TIMING OF INTERFACE WITH MICROPROCESSOR AND PULSE INTEGRATION BY SIGNAL PROCESSOR

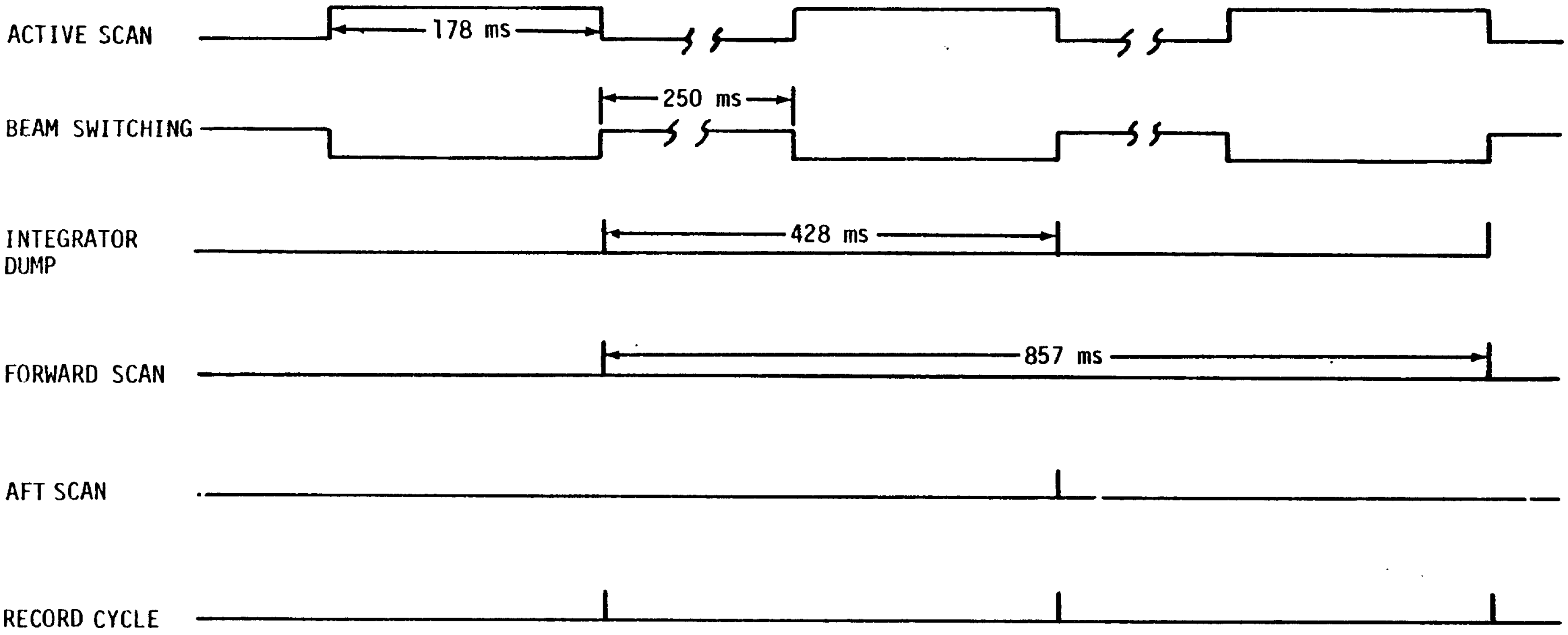


Figure 3-3

INTERFACE CONFIGURATION EMPLOYING A MICROPROCESSOR BUFFER

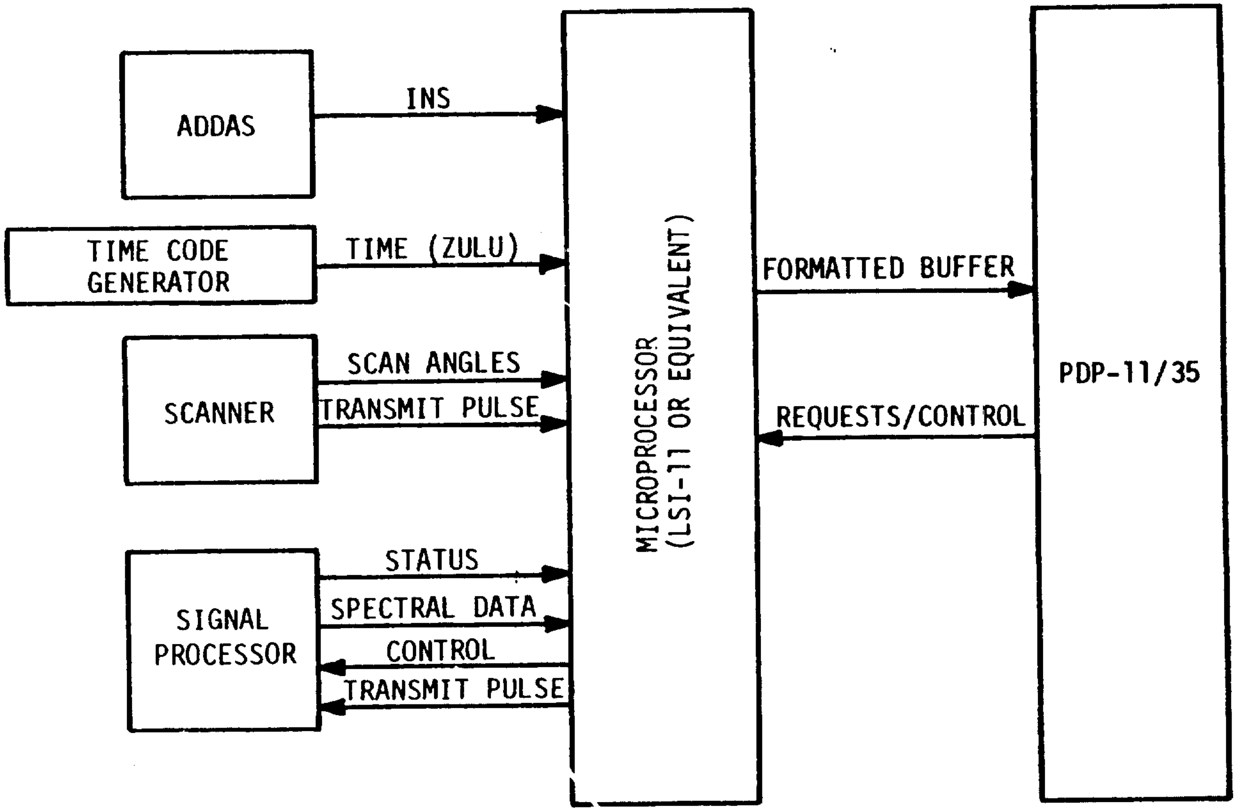


Figure 3-4

4. DATA STORAGE

The choice of data storage schemes is dependent upon several interrelated factors, such as, the volume of data to be gathered to perform the required function, the number of intermediate variables required for final computations, the data rate of the incoming data which directly impacts the available computation time, and the available address space provided by the computer architecture. Although only estimates of certain parameters can be attempted without a detailed analysis of the total software system, conservatism in making the estimates can approximate the worst case storage requirement. In order to arrive at the storage estimates, an examination of the input data (the givens) and of the computations required to perform the flow field analysis is mandatory. The presentation of the algorithmic process can be found in Section 5, therefore only brief references will be made here to clarify the data storage discussion.

4.1 Input Data

The lidar signal processor performs poly-pulse pair estimation of the mean intensity (M_0), the mean velocity (M_1), and the mean spectral width (M_2) for each of n range cells along the line of sight for each transmitted pulse (n is a function of pulse width and range gating). For the purposes of this discussion, n is assumed to be 64 (found by pulse width = one microsecond, range gating from 1 km to 10 km), pulse integration will be performed by the lidar signal processor (25 integrations), the timing will be as shown in Figure 3-3. The total spectral data available every integration period is 192 words. Additionally, status information such as pulse width, minimum range, and range increment are included in the pulse information yielding 194 words from the signal processor. Information from the lidar scanner includes the direction cosines of the angle the transmitted beam makes with the longitudinal axis of the aircraft referenced to true north. Certain aircraft and positional information is required to locate points of intersection of the forward and aft-looking scans. This data includes current latitudinal and longitudinal coordinates, altitude and heading. The data must be time tagged with the time of transmission to properly account for temporal changes in the phenomena. The total estimated requirement for input data, then, is 120 words per pulse integration period. An example of the data format is presented in Figure 4-1.

4.2 Data Volume

The maximum data storage volume requirements for the SSMS is the next system factor to be examined. The definition of the area of coverage during a single pass of the storm being

DATA STORAGE DEFINITION PER PULSE INTEGRATION PERIOD

HEADING	
LATITUDE OF ORIGIN	
LONGITUDE OF ORIGIN	
DIRECTION COSINE (X)	
DIRECTION COSINE (Y)	
LATITUDE - CURRENT POSITION	
LONGITUDE - CURRENT POSITION	
ALTITUDE OF ORIGIN	
ALTITUDE OF CURRENT PULSE	
SECANT OF SCAN ANGLE	
Y-INTERCEPT	
SLOPE OF LINE OF SIGHT	
TIME OF PULSE	HOURS
TIME OF PULSE	MINUTES/SECONDS
TIME OF PULSE	MILLISECONDS
PROCESSOR STATUS	WORD 1
PROCESSOR STATUS	WORD 2
PAD	
RANGE BIN NO. 1	M_0
	M_1
	M_2
•	
•	
•	
RANGE BIN n	M_0
	M_1
	M_2

Figure 4-1

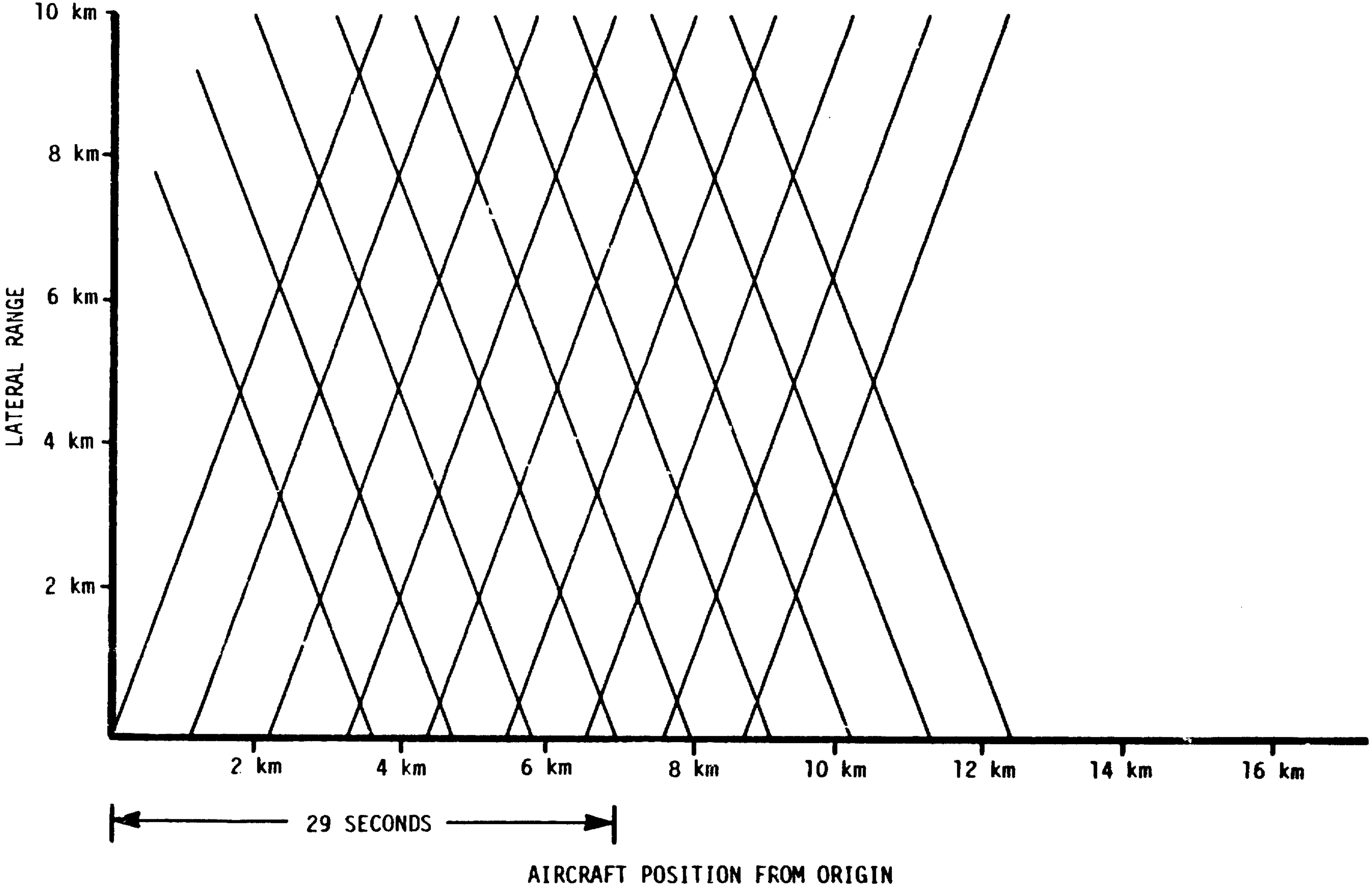
studied is 10 km along a line-of-sight in either direction. For a forward-looking scan (+20 degrees) to be intersected by an aft-looking scan (-20 degrees) at maximum range (10 km) requires approximately 29 seconds (for aircraft velocity of 235 m/sec). Figure 4-2 provides a graphical view of the intersection timing considering a straight and level flight path and an aircraft velocity of 235 meters per second. To provide transverse coverage of 10 km for flow field mapping would require an additional 40 seconds, making a maximum of fly-by time on the order of 67 seconds. With scan times of 178 milliseconds and beam positioning time of 250 milliseconds, there would be a maximum of 32 intersections for which data point registration would be required at any one time. Since the critical "look" for data registration is in the aft direction, only the most recent aft scan data need be maintained in memory for computation purposes. Each of the forward scans which are possible candidates for data registration (32) must be maintained. The resulting bulk storage for raw input data, then, is approximately 7,000 (7K) words. By contrast, the scan pattern described in the base configuration suggested a ±30 degrees scan angle which would have required approximately 40 seconds for intersections to occur at maximum range and would have as many as 64 possible intersections. The resulting bulk storage for raw data would then essentially double to require approximately 15K words of memory.

4.3 Intermediate Variables Storage Requirement

Certain computations in the analysis of two-dimensional flow fields require the use of intermediate variables for use in later computations. Certain other variables are required for program control and subroutine linkage. It is reasonable to estimate the storage requirements for these variables as 1K words. Additionally, there will be a requirement for the storage of program dependent constants, plot coordinate buffers, ASCII strings for operator communications, and the like. A very conservative estimate for these parameters, dependent largely upon the complexity and sophistication of the real-time software, is 4K words.

4.4 Available Address Space

The PDP-11/35 currently in use for the CAT program contains 64K words core memory. The 16-bit architecture allows direct addressing of only 32K words; however, the memory management option of the PDP provides for extended address capability to 18-bits or 128K words. The memory management function provides for a task to reside anywhere within the available memory, however, any given executable task may still only address 32K words of memory. With the data storage requirement of approximately 20K words (worst case) only 12K words would be available for



SCAN PATTERN WITH 40° GRID

Figure 4-2

executable code within a given task. The effective address space of a task may be extended by the use of a memory management capability known as "regions." The data from the lidar interface could, for instance, be mapped into two 8K regions. Each region could be mapped into the tasks address space when needed but at the expense of the overhead required to maintain the regions, both by the executing task and the operating system.

The data storage requirements for the system as currently defined do not appear to pose any significant problems. It is important to note that the driving consideration in estimating the data storage is the scan angle. The greater the angle of scan, the longer the time required to intersect the lines-of-sight at maximum range, and, hence, the greater the amount of data storage required to maintain sufficient forward scan data to perform the flow field computations.

5. DATA PROCESSING

The development of a two-dimensional flow field map in real-time on a single processor requires (1) that the data be efficiently stored for optimum access times, (2) that the algorithms involved can tolerate errors in precision, and (3) that there is sufficient time to perform processing on the worst case set of data input. It has been shown that the data can be stored in a manner which makes data access efficient (Figure 4-1). It has also been shown that there is sufficient time (Figure 3-3) to perform the flow field computations. It now remains a task to examine the processes involved in the registration, correlation, and flow field resolution of the input data within the framework of the current system. The discussions which follow rely heavily on the supposition that an interface "black box" microprocessor will perform some of the preliminary computations required to facilitate the flow field computations.

5.1 Review of Data Processing System Concept

In order to map a two-dimensional flow field, it is necessary to obtain two independent measurements of the same spatial volume. In the severe storms system, this can only be accomplished by scanning first in one direction (i.e., forward) and, at some later time determined by aircraft velocity, scan angle, beam switching time, and maximum range, scanning in the opposite direction. A simplified graph of the measurement philogophy is presented in Figure 5-1. For a straight and level flight path the angles (Θ_1, θ_2) between the transmitted beam and the longitudinal axis of the aircraft would be equal. Likewise, the ranges (R_1,R_2) would be equal. The point of intersection (X,Y) and the velocities along the respective lines of sight would be readily obtainable by well-known methods.

It is unlikely that the aircraft will be able to maintain a straight and level path due to turbulence, wind components, and normal aircraft instabilities. Any two measurements at the same range along opposite lines-of-sight then may not, in actuality, intersect; rather the point of intersection will be skewed somewhat by the effects of the drift angle, the angle between the desired track of the aircraft and the actual track. A glance at Figure 5-2 will amplify this statement. The problem during the data processing phase is to locate the actual points of intersection and to correlate the returns along the respective lines of sight within some correlation radii. The analysis process must then resolve the respective lines of sight velocities into a flow field component and appropriately format the result for display. An additional process is involved in correctly locating the intersection points; namely, correcting for movement in the storm location between the two measurements given some initial location of the storm cell and a velocity vector indicating the magnitude and direction of movement.

SIMPLIFIED SCAN GEOMETRY

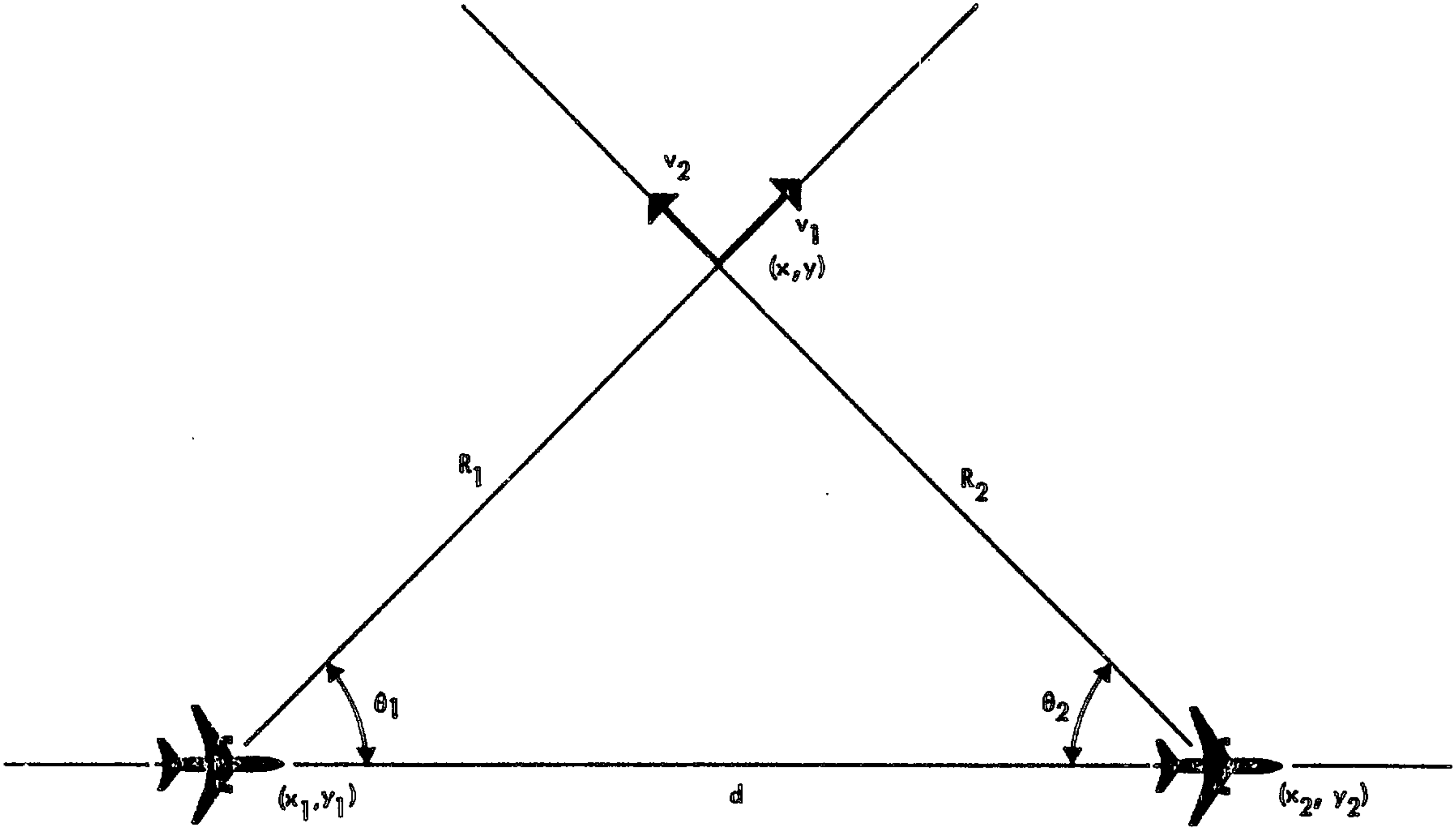


Figure 5-1

ILLUSTRATION OF AIRCRAFT POSITION ABERRATIONS TO LINE-OF-SIGHT

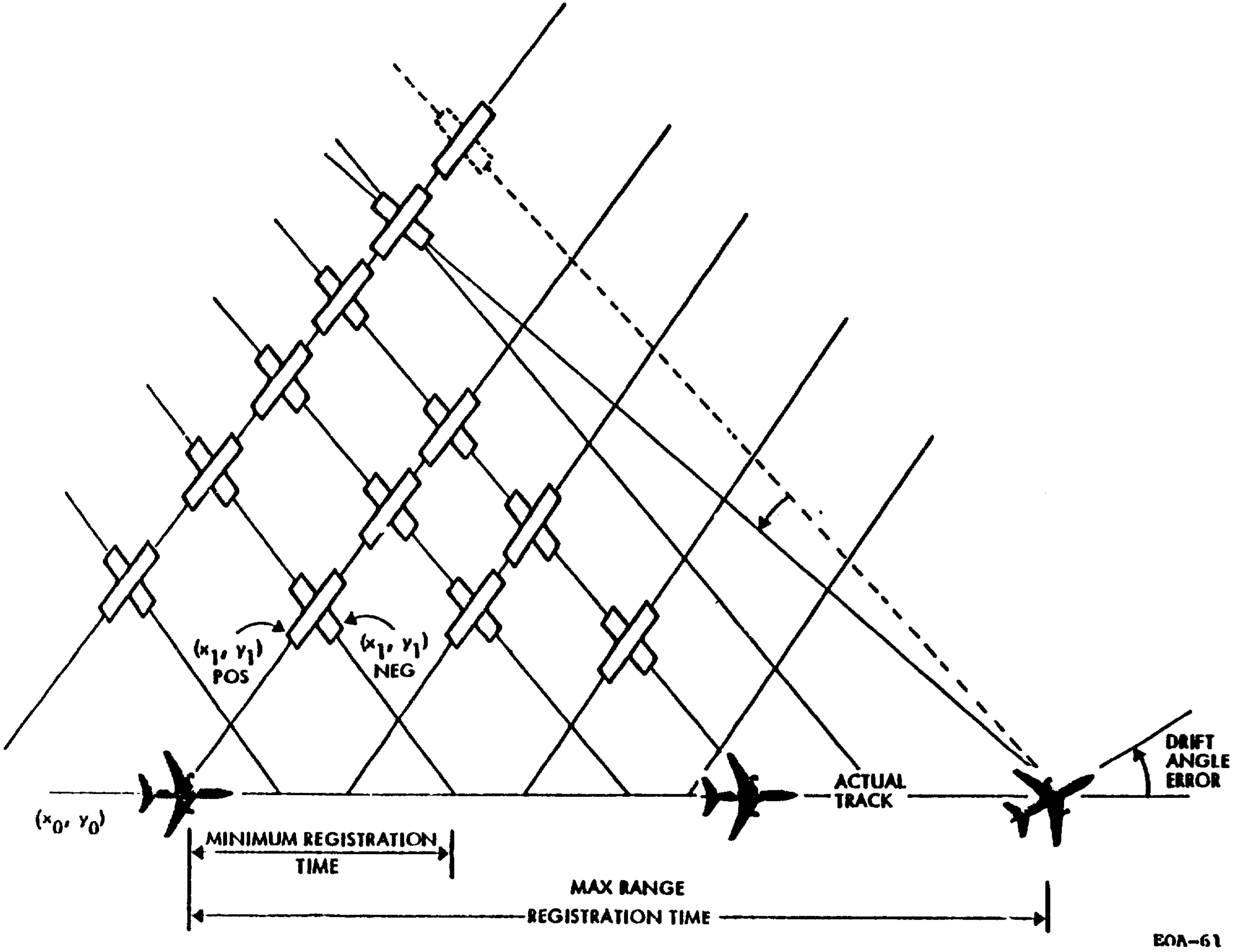


Figure 5-2

5.2 Data Registration

The methodology of velocity flow field computation as presented in Sections 4.5.3 and 4.5.4 of the Raytheon report was examined with consideration of possibly simplifying some of the computations and expanding upon the detail slightly to arrive at a workable real-time solution. The primary objective in real-time is to obtain a gross measure of the flow fields rather than very accurate representations that could be used for later analysis. To this end, the discussion which follows focuses on those analyses which may be performed in real-time, and which provide a useful presentation of the data (a flow field map) to indicate approximately what and where things are happening. It should be noted that the equations presented below will also satisfy the postanalysis phase; only the precision of the computations are affected.

Given the data input as shown in Figure 4-1 for each of n forward scans and the most recent backward scan, we can begin the registration process.

First the location of the point of intersection of the two lines-of-sight must be calculated or defined. Since the Y-intercept and the slope of each line-of-sight has been previously calculated by the microprocessor, the coordinates for the point of intersection may be obtained simply by

$$X_p = \frac{Y_{I_{AFT}} - Y_{I_{FWD}}}{M_{FWD} - M_{AFT}} \qquad (5-1)$$

$$Y_p = Y_{I_{FWD}} + M_{FWD}X_p$$

where Y_I represents the Y-intercept and M represents the slope. FWD and AFT refer to the respective line-of-sight. Appropriate error checks on the respective altitudes of the original data points may possibly cause an intersection calculation to be dismissed. It is not felt at this time that altitude variations will be significant enough to reject a scan candidate; however, the check should be made prior to the performance of 5-1 and 5-2.

Once the point of intersection (X_p, Y_p) is found, the range bin from the candidate scan must be computed. The computation is necessary since (as shown in Figure 5-2) the aircraft flight path will have normal aberrations causing deviations from the desired track. This computation takes the form

$$B_{r_i} = X_p \text{ Sec } \Theta_i/150*PW \qquad (5\text{-}3)$$

where B_{r_i} represents the range bin of the line-of-sight (forward or aft) currently being computed.

X_p - represents the X coordinate of the intersection.

Θ_i - represents the "look" angle with respect to true north.

P_w - represents the pulse width (in usec).

150 - is a constant for the range resolution of the system.

The velocity along the line-of-sight may be obtained by dividing the first moment (mean velocity - M_1) for the range bin by the zeroth moment (mean intensity - M_0)

$$V_{LOS_i} = \frac{M_{1_{LOS_i}}}{M_{0_{LOS_i}}}$$

Given the velocity along the line-of-sight and the direction cosines for the line-of-sight, the velocity vector may be obtained. At this point it should be noted that the reference coordinate system is assumed to be in terms of latitude (ϕ) and longitude (λ). For the geographic area of interest and the short durations of a fly-by, the direct usage of a ϕ,λ system appears most efficient. By maintaining the ϕ,λ of the origin of the fly-by and computing a relative position in meters, there is no need to perform time-consuming coordinate conversion processes. The computation of the flow for any given point of intersection then becomes a simple vector addition, yielding both magnitude and direction.

Corrections for the movement of the storm during this process have been deliberately omitted. Although these corrections may be rather easily added to the computations, further analysis of the contributions of storm motion to the data correlation process is required. As in the Raytheon report, the correction for storm motion would take the form

$$V_s = <\Delta X, \Delta Y> \tag{5-5}$$

where V_s is the storm velocity vector and ΔX, ΔY represent the velocity vector components.

Variations in position then become

$$D_{sx(y)} = \Delta t \ \Delta x \ (\Delta y) \tag{5-6}$$

where Δt represents the elapsed time from the origin of the fly-by. Subtracting the resulting deltas from the coordinates of the line-of-sight return would effectively translate the point to the initial position of the storm.

5.3 Error Checks

During the registration/correlation process, certain error limits must be defined to prevent erroneous computation of scan intersections and velocities. Since there will be aberrations in the flight path, scans will not necessarily intersect at convenient ranges. Depending upon the pulse width, data from regions of up to 1,200 meters will be contained within a single range bin. A decision as to the correlation radius for acceptable intersection points must be made. If all points within a scan are considered valid and if we assume a maximum registration time of approximately 30 seconds, there will be less than 40 possible points of intersection along any given aft scan - not a significant number. The value of error limits then, is not in reducing the computation time, but in providing reliable, meaningful computations and display of the flow field.

6. ERROR ANALYSES

In addition to performing the studies associated with data processing and storage requirements of the base configuration and suggested modifications for the Severe Storm Measurement System (SSMS), an attempt has been made to assess the potential performance of such a system with respect to the potential errors that can be experienced by the measurement system. These error analyses have been performed with the intent of pointing out the magnitude of the potential errors and identifying areas where corrective measures are mandatory in order to acquire useable velocity flow field data. The error analyses were not scoped to include a recommended solution, only to point out potential problems.

The analyses were performed in a simplified format to correlate with the level of effort and were formulated as a function of their potential source. The potential errors were anticipated to originate from the following sources:

1. The Aircraft's Inertial Navigation System (INS), which includes otuputs of latitude, longitude, altitude, pitch, roll, and yaw.
2. The storm motion and changing meteorological conditions in the storm.
3. The scanner, including the base configuration and the newly proposed wedge scanner.
4. The processor.
5. The data processing system.
6. The laser.

As described in the base configuration, the SSMS is assumed to operate to a maximum range of approximately 10 km with a minimum pulse length of one microsecond and a maximum pulse repetition frequency of 200 Hz. This results in a line-of-sight range scan which has approximately 64 range bins of 150 m range resolution with a minimum range measurement capability of approximately 1 km.

The Convair 990-type aircraft is assumed to have operating airspeeds between 100 and 250 m/sec. The airspeed of the aircraft and the pulse integration of the system (from 1 to 100 pulses) is used to create the desired scan pattern for severe storm velocity flow interrogation.

Using the above and preceding information, the error analyses were performed and will be documented in the following subsections.

6.1 Aircraft - INS Induced Errors

From section three of the referenced Raytheon final report (1), the INS for the aircraft has the following characteristics:

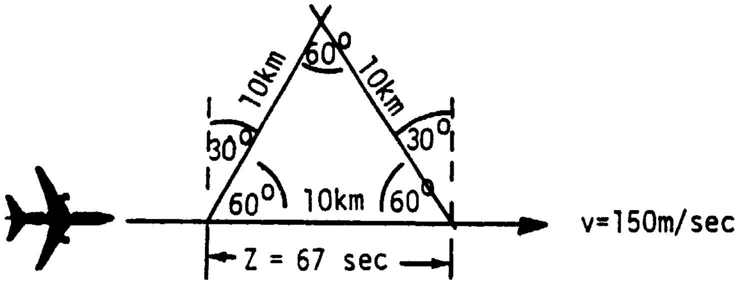
1. The INS drift rate is such that indicated latitude and longitude may be in error by as much as 1.0 nautical mile in one hour (Drift rate = 1.0 min/hr.).
2. The aircraft altitude is determined by the pressure altimeter and by a radar altimeter.
3. The aircraft roll indicator output from the INS has 1σ heading errors of 0.7° in smooth air with a resolution of ~0.03° and an accuracy of 0.2° to 0.5°. In the vicinity of turbulence, the aircraft exhibits a 1σ standard deviation of 1.0° roll about the mean.
4. The aircraft pitch indicator output from the INS has 1σ heading errors of 0.1° in smooth air with a resolution of ~0.03° and an accuracy of 0.2° to 0.5°. In the vicinity of the turbulence, the aircraft exhibits a 0.32° (1σ) standard deviation about the mean pitch angle.
5. The aircraft yaw indicator output from the INS has 1 heading errors of 0.2° in smooth air with a resolution of ~0.03° and an accuracy of 0.2° to 0.5°. In the vicinity of turbulence the aircraft exhibits a 0.4° (1σ) standard deviation about the mean yaw angle.

Since the purpose of the SSMS is to perform velocity measurements in the vicinity of storm systems, it is anticipated that the aircraft will be operating in the vicinity of turbulence. It is for this reason that the turbulence condition, roll, pitch, and yaw estimates of variation about the mean have been used in estimating the positional variations in velocity data points taken by the SSMS. If the turbulence is more severe than that referenced above, then it is expected that the standard deviations would increase resulting in larger variations of the mean heading angles.

6.1.1 The Errors Resulting from INS Drift

The referenced Raytheon final report (1) and Physical Dynamics Report No. NAS8-31724 (2) indicates that major features of the storm should not change significantly within 2-5 minutes. It is assumed that the timewise extent of an aircraft fly-by data take is limited by the internal change rate of the storm, since the data points associated with the forward scans must correlate spatially and meteorologically with the crossing backward scans.

If an aircraft velocity of 150 m/sec is assumed and the base configuration scan angles of ±30° is used, then the time between maximum range points (10 km) that exhibit spatial correlation will occur at ≈67-second intervals.



This is significantly under the 2-5 minute anticipated limit for a data take.

The INS drift rate of 1.0 nautical miles/hour (~0.5/m/sec) would result in a position error of ~34 m for the maximum range data points mentioned above. The drift rate induced error for a five-minute data take would result in positional errors of ~152 meters for individual data points.

These errors could be significant to an SSMS that is operating at 1 µsec pulse widths, range resolution of 150 m. It may be possible to improve on this INS operating characteristic by initializing on the starting latitude and longitude for a given data take and (using aircraft heading and velocity information) calculating the data point positions (in a desired coordinate system) using the data processing system (which could include a preprocessor/microprocessor).

6.1.2 The Error Resulting from the Aircraft Altitude Indicator

The aircraft altitude is controlled through the use of two altitude sensing devices. The radar altimeter which is very sensitive to fluctuations in ground terrain and is not directly referenced to sea level altitude and the pressure altitude altimeter.

The radar altimeter would not be a good altitude indicator for the SSMS since the ground terrain in the vicinity of all storm activity cannot always be guaranteed to be flat and/or well known. Ground elevation changes of 150 m would cause the radar altimeter to indicate a change in aircraft altitude of 150 m when in reality the scan plane for the SSMS should remain unchanged.

The pressure altimeter, which relates the aircraft altitude to sea level altitude, is the ideal indicator to be used to ensure the aircraft remains in a constant horizontal plane. However, in the presence of severe storms, it is known that rapid fluctuations in barometric pressure take place, both temporally and spatially. It is for this reason that altitude errors have been addressed.

In the vicinity of severe storms the barometric pressure may change by several millibars in a period of 60 seconds or over a distance of a few km. If the aircraft is operating on autopilot, this will cause an altitude correction to be executed and will result in a tens of meters altitude error being introduced to the subsequent scan plane data points. The altitude errors introduced by such fluctuations in barometric pressure are directly proportional to the magnitude of the pressure fluctuation.

Such an error may be circumvented by initializing the data take with a given altitude and integrating the vertical accelerometer outputs along with aircraft heading information to derive the altitude history for the data take.

6.1.3 Errors Resulting from INS Roll Indicator

In the vicinity of turbulence the standard deviation (1σ) in roll can be expected to be $\pm 1°$ in magnitude. This variation in roll orientation of the SSMS platform, the aircraft, can cause the data points of the horizontal scan plane to be spread over a 349 m vertical plane at the maximum range of 10 km. This displacement will prohibit many of the data points from being used in the calculation of velocity flow field since spatial correlation cannot be achieved between many forward and backward-looking line-of-sight data points. This deviation should not result in flow field measurement errors since the data point displacements are known and properly handled.

The more significant problem associated with the INS roll indicator is its 0.5° accuracy. The 0.5° measurement accuracy of the INS roll indicator can result in a measurement error of ~87 m at the maximum range of 10 km. This error represents 58 percent of the 1 μsec pulse width range resolution of 150 m and is marginally acceptable.

The significance of this displacement error can be reduced by decreasing the range resolution or shortening the scan range of the system.

The number of data points that can be expected to spatially correlate in the horizontal scan plane can be increased significantly by incorporating a roll correction mechanism into the SSMS scanner. Such a corrective mechanism has been proposed by Raytheon as an update to the base configuration scanner. The potential errors associated with this scanner will be discussed in Section 6.3.

6.1.4 Errors Resulting from INS Pitch Indicator

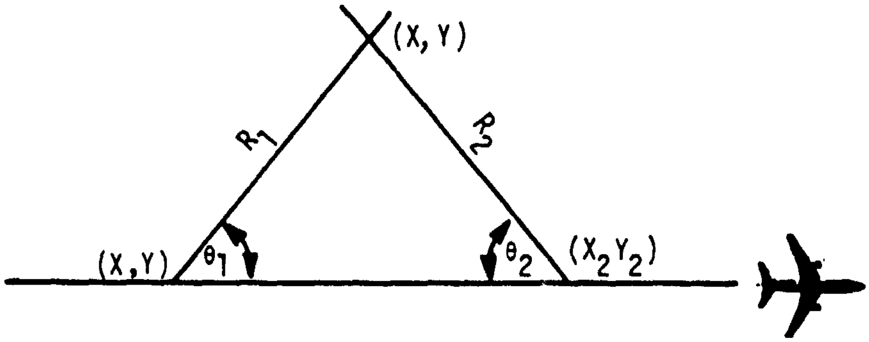
In the vicinity of turbulence, the standard deviation (1σ) in pitch can be expected to be ±0.32° in magnitude. This variation in pitch orientation of the SSMS platform, the aircraft, can cause the data points of the horizontal scan plane to be spread over an ~ 56 m vertical plane at the maximum range of 10 km.

This displacement will not prohibit data points at the maximum range from spatially correlating since the spread represents ≤37 percent of the one microsecond pulse width range resolution. Even though this deviation is less significant for pitch than roll, it can be removed using the same corrective scheme that is being employed for roll correction. Raytheon has proposed that the pitch correction also be made with the updated scanner design and such an improvement is underwritten by this analysis. The more significant problems associated with the INS pitch indicator is its 0.5° accuracy. The 0.5° measurement accuracy of the INS pitch indicator can result in a measurement error of ~43 meters, at a range of 10 km. This error represents ~29 percent of the 1 μsec pulse width range resolution and is acceptable.

The significance of this error can be further reduced by decreasing the range resolution or by decreasing the scan range of the system.

6.1.5 Errors Resulting from INS Yaw Indicator

In the vicinity of turbulence, the standard deviation (1σ) in yaw can be expected to be ±0.4° in magnitude. This variation in yaw orientation of the SSMS platform, the aircraft, can cause the data points of the horizontal scan to be incorrectly positioned in the horizontal scan pattern. The ±0.4° standard deviation in yaw will result in a ±70 m spread about the mean range line-of-sight at the maximum range of 10 km. This displacement in line-of-sight range scan can be accounted for in calculating the forward and backward scan crossing points by correcting θ, and θ_2 for yaw at the time of range scan 1 and range scan 2.

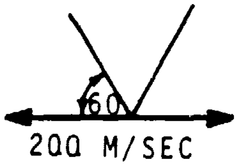


It is suggested that the deviation in yaw heading be accounted for through the data processing system, possibly in a preprocessing microprocessor.

The measurement accuracy of the yaw indicator is given as 0.5° and can result in a positioning error of ~87 m at the maximum range of 10 km. This error is ~58 percent of the one microsecond pulse width range resolution and is marginally acceptable. The significance of this error can be reduced by reducing the maximum range for the range scan and increasing the integration time.

The magnitude of the velocity error to be derived from errors associated with yaw heading errors should be well within the velocity resolution associated with a 1 μsec pulse width. The angle and position errors introduced by the INS are much more significant as they relate to the spatial correlation of data points than as they relate to the angle error effects on the magnitude of the measured Doppler velocity. As an example, a 1° error in line-of-sight with respect to a velocity flow field will result in a Doppler velocity error of less than 0.2 percent.

The aircraft velocity component of the SSMS's Doppler frequency must continually be monitored and removed. Changes in yaw heading will result in slight changes in the aircraft contribution to this Doppler velocity. The standard deviation in yaw will result in ±1.2 m/sec shifts in Doppler velocity contribution from the airplane traveling at 200 m/sec.



$$\text{COSINE } 60^\circ = \frac{X}{200}$$

6.2 Storm Motion Induced Errors

The SSMS velocity measurements of the storm can be significantly degraded when data is taken on a rapidly moving storm system without accounting for such motion between the observations of a forward and backward scan that correlate spatially. The significance of spatial correlation in calculating the velocity components of a given position in space is the assumption that the velocity flow field for that point had not changed significantly during the measurement interval. In the case of a rapidly moving storm, the flow field is likely to move along with the storm. Thus, the problem of correlation becomes one of spatially tagging some major feature of the storm, which correlates with the general velocity flow, and taking account of this movement between fro and aft range scans that have correlatable data points.

An example of the errors that may be introduced by unaccounted for storm motion is as follows: For a storm system moving at 20 nautical miles/hour (~10 m/sec), the position change of the storm can result in considerable errors in velocity data points correlation between the maximum range data points. For an aircraft moving at 200 m/sec and making observations to a maximum range of 10 km, with scan angles of +30°, the time between maximum range data points correlation is 50 seconds. This implies the storm system with its localized structure may move 500 m between maximum range correlated data point takes or 3,000 meters during a given storm fly-by of five minutes. This movement, unless accounted for, has the potential to cause the calculation of spatially correlated velocity data to be meaningless since the velocity flow field structure may have changes, significantly between data takes.

The significance of this error may be reduced by decreasing the range resolution to the order of storm movement or by decreasing the maximum operating range.

In rapidly moving storms, it may be undesirable to make velocity measurements unless the storm movement is monitored and accounted for.

Several techniques for monitoring and accounting for gross storm feature movements are aircraft-based radar, ground-based radar, and the signal strength information resulting from the SSMS. These storm system measurements may be required to have their velocity flow field data analyses performed in a postprocessing mode. The reason for this being the task of hardware interfaces to radars and/or software to account for the movement of the storm in the data processing.

6.3 The Scanner Induced Errors

The base configuration scanner which operates by switching a mirror to direct the beam from 30° forward of the perpendicular to flight to 30° backward of the perpendicular to flight in the horizontal scan plane is shown in Figure 4.6 of this referenced Raytheon document.

The specifications for this scanner are outlined as follows:

SEVERE STORMS MEASUREMENTS 2-D SCANNER
(Two Look)

Scan Mirror

Size:	14 inches diameter
Material:	Magnesium Honeycomb
Figure:	$\lambda/10$ 10.6 microns
Coating:	Nickel plating with electrolytic gold coating

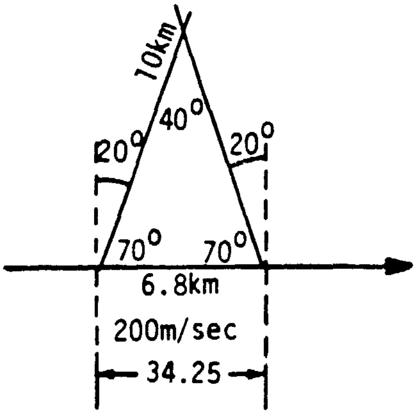
Scanner

Mirror Rotation $(\dot{\theta})$	
Azimuth	30°
Roll	+1.5 (optional)
Maximum Velocity $(\dot{\theta})$	$\bar{2}.5$ rad/sec
Maximum Acceleration $(\ddot{\theta})$	50 rad/sec^2
Position Error $(\Delta\theta)$	+0.3°
Scan Time	$\bar{0}.2$ seconds (beam goes 30° aft to 30° forward)
Settling Time	20 m/sec to ±.3° and 12.5°/sec

The specification for the scanner will result in positioning errors of the maximum range data to ±52 m where maximum range is taken to be 10 km. This error represents ~35 percent of the range resolution of a 1 μsec pulse width and is considered acceptable. The significance of this error can be further decreased by the range resolution with a longer pulse width. There will be high frequency aircraft vibrations which will effect the scanner positioning accuracy, but they should be very small in amplitude and should not result in significant positioning errors.

The newly-proposed SSMS scanner which utilizes two rotating germanium wedges will have the potential to create scanning errors due to inhomogenities in the index of refraction, rotation errors in the wedges, lack of flatness in the wedge surfaces, etc. The rotating wedge scanner is defined in great detail in Raytheon Monthly Progress Report No. 2 for NAS8-33120 and in Phase I Design, Raytheon Report for the Airborne Lidar Scanner, January 25 and 26, 1978(3).

The specifications for the wedge scanner have been analyzed and appear to be adequate to provide the required scanning capability for the SSMS. The two wedges each have a 3.33° slope and provide a maximum deflection of the transmitter beam of 10.65°. This reduced deflection/scan angle will have a chain reaction effect on the entire system operating characteristics such as scan pattern, time between correlation of maximum range scan data points, and velocity component calculations.



The newly proposed scanner will have the capability to remove the effects of aircraft roll and pitch from the SSMS range scan data points. The scanner will be capable of maintaining the range scan in the desired horizontal plane to within the accuracy of the INS and the altimeter indicator. This has the potential of eliminating the need to ignore out-of-tolerance data points from the system's scan plane. The errors associated with yaw will still require corrective calculation measures, but potentially can be handled in the system's data processing system or preprocessor/microprocessor.

The extent of the errors to be introduced by the rotating wedge scanner can be better estimated following laboratory testing of an engineering model.

6.4 The Processor Induced Errors

The base configuration digital data processor was defined to be responsible for assembling the frequency data from the laser Doppler system, processing to determine the signal intensity (zeroth moment), the average velocity (first moment), and the variance or width of the velocity spectrum (second moment) for each range resolution cell. The processor was to be designed to operate at all pulse repetition rates and pulse widths associated with the present CAT and the TEA transmitter. Additionally, it was to have the capability of variable pulse integration from single pulse to ~100 pulses.

Using the base configuration definition of the processor, it is difficult to assess or assign specific errors that can be attributed to the processor. The integration of data points will tend to increase the signal-to-noise ratio at a rate $\approx \sqrt{n}$ where n is the number of integrations. This increase signal-to-noise will tend to increase the range resolution capability of the system which reduces errors. The processor basically is designed to reduce errors in the system and with the present visibility into its specific functions, an error analysis is not possible.

The newly proposed Doppler Lidar Signal Processor as defined in Lassen Research Monthly Progress Report No. 1, NAS8-33389, January 1978 (4), has not been thoroughly analyzed at this writing. An error analysis on the proposed processor should be performed at a later date when the design has reached a more mature stage.

6.5 The Data Processing System Induced Errors

The base configuration for the data processing system, DPS, of the SSMS employs a PDP-11/35-type computing system. The data processing system is assumed to perform a number of functions. First, it calculates the velocities from the three moments available from the processor and stores them in the appropriate locations, along with the supplementary data required to perform the registration analysis. The next step locates the position and orientation of the aircraft at the time of data collection and references it to the initial position of the storm and stores the information for later use. The velocity flow field is generated by first finding the coordinates of each point at which a forward and backward scan cross, and then identifying the correct range bin along each line-of-sight so that the appropriate line-of-sight velocity data can be obtained. (This area of processing contains the most likely contributor to error in calculation of velocity flow field components.) The analysis of the control parameter, correlation radius, which will limit the error has not been performed and would most appropriately be a part of a total system simulation study for the SSMS.

The DPS will be used to resolve these spatially correlated velocity flow field components into the desired coordinate system and to display them in a suitable fashion.

This data processing will be performed to some degree in the aircraft (in real-time). In addition, the DPS will be used to perform a higher fidelity data analysis in a postflight data processing mode.

The errors that could be attributed to the DPS will originate from the correlation algorithm and radii that is used in data point correlations and from data registration errors associated with the data centroiding algorithm.

The spatial centroiding of velocity data points required due to finite range resolutions, aircraft motion and integration is an operation that could be assigned to the preprocessing/microprocessor and as such reduce the data processing load for the DPS.

The analysis which could determine the requirement for correlation radii in performing the spatial correlation of data points has not been performed for the SSMS to date. However, previous experience with focused Laser Doppler Systems have indicated that it is a function of the system's range resolution and the meteorological operating conditions (velocity gradients with time, space, and direction).

The other errors that occur in the DPS should be much less significant than the errors previously mentioned in Sections 6.1, 6.2, 6.3, and 6.4.

The DPS is presently immature in design definition but will have a design goal to accomplish the requirements of the other SSME subsystems and the total SSMS without introducing additional degradations to the system's measured Doppler data.

6.6 The Laser Induced Errors

The SSME will require a laser subsystem that has the capability to make atmospheric measurements in the presence of alternating environments, to ranges in excess of 10 km. The laser will be required to operate at variable pulse widths from a minimum of one μ/sec and variable pulse repetition frequencies to a maximum of 200 Hz.

The prime system errors introduced by the laser are those derived from a lack of energy per pulse to yield a detectable signal from the desired range, a lack of coherency resulting in false or no Doppler velocities, and a lack of frequency stability resulting in anomalous Doppler frequencies being derived from the mixing of the return signal and the master oscillator.

The velocity errors introduced by the laser frequency instability occur in the following manner. A laser pulse is transmitted to the atmosphere and its reflected backscatter is received at the collecting optics at some selected time relative to the transmit time. The range to the backscatter volume is given by $r = c\Delta t$ where r=range to scattering center, c=the speed of light, and Δt is the time between transmit and receive. If the Δt=100 μsec, then the range to backscatter center (region from which the Doppler velocity is derived for the single pulse) 15 km. If the instability of the laser frequency is such that the master oscillator component changes frequencies by 300 Hz during the transit time Δt, then the Doppler frequency indicated by the SSMS will be in error by ~1.5 m/sec.

The probability of the error or the magnitude can be decreased by decreasing the operating range/transit time. The significance of the error can be decreased by decreasing the velocity resolution such that frequency shifts in the master oscillator will not be sufficient to take the reflected frequency out of the picture.

The performance of the laser, in terms of operating power or energy per pulse can be used to increase the range resolution and velocity resolution by increasing the S/N for a given range.

7. CONCLUSIONS AND RECOMMENDATIONS

This section provides a summary of the major conclusions derived from the study and includes preliminary recommendations for system data acquisition, data storage, data processing, and reduction of system errors. Additionally, recommendations are made for further analysis and study efforts to be undertaken with the development of a system simulation which includes data processing algorithms.

7.1 Conclusions

The following conclusions are derived from the study of the data acquisition requirements for the Severe Storm Measurement System:

1. The acquisition of spectral data (from the lidar signal processor), aircraft position data, angle of scan (scanner output) data, aircraft orientation data, and storm motion data are required in the calculation of two-dimensional flow field information on the severe storm.

2. The acquisition of this data will require several independent interfaces to the computer using the base configuration definition of the system.

3. The base configuration mode of interfacing with the signal processor does not allow sufficient time to permit data transfer of the aircraft position-orientation and spectral data and completion of the formatting and signal processing. An alternate method of data acquisition and interfacing must be found.

4. Direct Memory Address (DMA) between the signal processor and the PDP-11/35 will significantly reduce the time required for lidar data transfers. Since DMA devices correspond directly with no processor resources required, the transfers occur essentially at memory speeds. The total data transfer can be accomplished in less time than a single transfer under the base configuration scheme.

5. The addition of a microprocessor which could perform some of the requisite computations, accept the spectral data from the signal processor and scan position data from the scanner, and format a single buffer for direct memory address transfers at the completion of each integration period would greatly reduce the load on the PDP-11/35 and extend the time available for real-time processing of the flow field data.

The following conclusions are derived from the study of data storage requirements for the Severe Storms Measurement System:

1. The total estimated data rate for the system is 210 words per pulse integration period while using the one microsecond pulse width and operating to maximum ranges of ~10 kilometers.

2. The bulk storage requirement for the system when scanning ±30° about the perpendicular to the flight path is approximately 15,000 words of memory. This is reduced to approximately 7,000 words of memory when the scan angle is ±20°.

3. The storage requirements for Intermediate Variables will be approximately 1,000 words of memory.

4. The storage requirements for program dependent constants, plot coordinate buffers, ASCII strings for operator communications will be approximately 4,000 words of memory.

5. The data storage requirements for the system as currently defined do not appear to pose any significant problems.

The following conclusions are derived from the study of data processing requirements for the Severe Storms Measurement System:

1. The development of a two-dimensional flow field map in real-time on a single processor requires that the data be efficiently stored for optimum access times, that the algorithms involved can tolerate errors in precision, and that there is sufficient time to perform processing on the worst case set of data inputs.

2. Data processing algorithms which correct for aircraft flight path errors and for storm movement must be developed and included in the systems software.

3. Once data point correlation between forward and aft scans have been made, the computation of the flow field for that data point becomes a simple calculation.

4. A decision as to the correlation radius for acceptable intersection of data points must be made. However, additional system analysis will be required before a judicious decision can be made.

The following conclusions are derived from the Error Analyses that were performed relative to the operation of the Severe Storm Measurement System in the vicinity of turbulence.

1. The INS drift rate can result in significant errors for the system operating at one microsecond pulse length in the base configuration mode. It may be possible to improve on this INS operating characteristic by initializing on the starting latitude, longitude position and calculating position from that point based on aircraft operating parameters.

2. The aircraft altitude is an important parameter in the calculation of aircraft position and resulting velocity data points. Aircraft altimeters may not provide sufficient accurate altitude information in the vicinity of severe storms.

3. The INS roll indicator should provide sufficiently accurate information to permit calculation of two-dimensional velocity flow fields in the vicinity of a severe storm. The significance of the roll indicator related errors can be reduced by decreasing the range resolution and/or shortening the scan range.

4. The INS pitch indicator should provide sufficiently accurate information to permit calculation of two-dimensional velocity flow fields in the vicinity of a severe storm. The significance of the pitch error can be reduced by decreasing the system's range resolution and/or by decreasing the scan range.

5. The INS yaw indicator should provide sufficiently accurate information to permit calculation of two-dimensional velocity flow fields in the vicinity of a severe storm. The significance of the errors can be reduced by decreasing the maximum scan range and/or increasing the integration time.

6. The movement of the storm system which is being measured can cause significant errors in the calculation of velocity flow fields if such motion is not fully accounted for in spatially correlating the forward and aft range scan data points.

7. The base scanner design has the design specifications to permit it to provide adequate scan coverage with accuracy sufficient to permit the calculation of two-dimensional velocity flow field information in the vicinity of a severe storm. The newly proposed rotating wedge scanner has the design characteristics to permit even better defined/controlled Doppler data to be acquired for calculation of the velocity flow field than the base configuration scanner.

8. The data processing system should introduce no additional errors to the Doppler data collected from the laser, scanner, and INS subsystems. The correlation radius which is a data processing input parameter, is yet to be determined, but will influence the accuracy of the velocity flow field calculations.

9. The laser induced errors should be insignificant as they relate to frequency fluctuations (by design). It is of utmost importance that sufficient laser power be attained to permit high S/N ratios at the maximum operating ranges such that data acquisition, data storage, and data processing can be accomplished with confidence.

7.2 Recommendations

1. The recommendation for data acquisition is for the addition of a microprocessor which performs some of the requisite computations and serves as a single interface for DMA data transfers to the PDP-11/35. A configuration for the hardware interface is presented in Figure 3-4 of Section 3.

2. The recommendation for data storage is for the potential use of a memory management capability known as "regions" to increase the effective address space for any given task.

3. The recommendation for data processing is for the development of efficient data processing algorithms which are matched to efficiently stored data. It is also recommended that error limits be defined to prevent erroneous computation of scan intersections and velocities.

4. The recommendation for improving the INS position indication system involves the use of INS latitude and longitude outputs at initiation of the fly-by. Then, using initial conditions and, aircraft status information, calculate the aircraft position at the required data rate for the duration of the fly-by.

5. It is recommended that action be taken to monitor and measure the motion of the severe storm for which velocity flow field data is being taken and that this storm movement information be properly accounted for in the calculation of the two-dimensional velocity flow field.

6. It is recommended that laboratory tests be performed on the rotating wedge scanner to determine the degree to which the design meets the specifications.

7. It is recommended that additional analyses of the proposed Doppler Lidar Signal processor be performed as the design reaches a more mature stage. These analyses should be performed for the purpose of determining potential errors that it may introduce to the system.

8. It is recommended that every effort be made to increase the level of performance of the laser system to be employed in the Severe Storm Measurement System.

9. It is recommended that a simulation of the severe storms data processing functions, which take into consideration the meteorological requirements for data analysis and display, be developed and used for system analysis. This same tool should additionally be used for postflight data and system analysis.

REFERENCED DOCUMENTS

1. Study of Hardware Applications of Airborne Laser Doppler System for Severe Storms Measurement, Final Report, Contract NAS8-31721, Raytheon Company, February 16, 1977.

2. Conceptual Design of an Airborne Laser Doppler Velocimeter System for Studying Wind Fields Associated with Severe Local Storms, by J. Alex Thomson, Alan R. Davies, Klaus G. P. Sulgmann, May 1976, Final Report on NAS8-31724, Physical Dynamics, Inc.

3. Airborne Lidar Scanner Phase I Design Reviews, January 25 and 26, 1979, Raytheon Company viewgraphs used by permission.

4. Doppler Lidar Signal Processor, Design Outline, Contract NAS8-33389, Lasser Research, January 1979.