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EXPLORATORY MEETING ON AIRBORNE DOPPLER LIDAR WIND VELOCITY MEASUREMENTS


**Summary of a Meeting Held April. 1, 1980, at
NASA/Marshall Space Flight Center**

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I. EXECUTIVE SUMMARY

The following provides in outline format the major conclusions of the April 1, 1980, meeting on the MSFC Airborne Doppler Lidar Wind Measurement System :

- System has the capability to provide detailed flow measurements of meso- and microscale processes:

Convective processes

- Subcloud dynamics
- Entrainment
- Cloud turret dynamics
- Cold air outflow
- Warm air inflow
- Anvil cloud structure
- Cloud environment dynamics

Local circulations

- Sea and land breezes
- Mountain/valley flows
- Heat island effects
- Flow around terrain features
- Model verification "ground truth"

Waves and turbulence

- Gravity wave structure
- Clear turbulence
- Breaking waves
- Generation and dissipation
- Mountain waves

Atmospheric boundary layer

- Mean flows
- Turbulence characteristics
- Inversion dynamics
- Entrainment processes
- Organized large eddy structure

Aerosol dynamics

- Transport processes
- Entrainment and detrainment processes
- Flux of aerosol through tropopause and fronts
- Aerosol cloud structure

Engineering and aeronautical applications

Wind energy

Wind fields for aircraft takeoff and landing

Industrial aerodynamics

Pollution monitoring

Agriculture aviation spray technology

- System verification flights should be performed in cooperation with other field experiments to obtain "ground truth" data.
- Participation in planned **field** experiments will significantly increase scientific return from Doppler Lidar program.
- Participation in cooperative convective precipitation experiment (CCOPE) is strongly recommended.
- Utilization of Doppler Lidar in other than horizontal mode can yield important and needed data; e.g., vertical line of sight can produce data on entrainment processes occurring at top of convective clouds.
- Studies to examine feasibility of system for global measurement of wind from **space** should be pursued.

II. INTRODUCTION

This document summarizes the scientific interests in the MSFC Airborne Doppler Lidar Wind Velocity Measurement System as a result of a meeting held at the NASA Marshall Space Flight Center, April 1, 1980. The exploratory meeting on the system and its scientific applications is part of the objective of the Severe Storms and Local Weather Research Program of the NASA Office of Space and Terrestrial Applications (OSTA). The applicable goals and objectives of the NASA Severe Storms and Local Weather Research Program are stated in this section to provide a frame of reference for this report. It is within this framework that the near-term (2-3 years) development and application of technology for the remote observation and measurement of wind will be pursued. However, it should be noted that in the context of the NASA Global Weather Research Program there is a long-term goal to remotely measure wind from space, ultimately to provide information on global wind fields for use in global circulation models. Thus, the MSFC Airborne Doppler Lidar System is an evolutionary one, with the ultimate goal being to remotely measure wind from a space platform. However, the necessary research and development that lead to the space flight system will take place in a series of steps wherein a Doppler Lidar system may evolve provided the applicable technology can be demonstrated. As the Doppler Lidar system evolves, it will be used to perform scientific research within the context for which it is best suited. Of course, the Doppler Lidar system evolution will be guided and planned with OSTA Program goals and objectives in mind. In the near term (next 2-3 years) the Doppler Lidar system will have range and resolution capabilities that will be ideally suited for the airborne observation of wind fields associated with severe storms and local weather phenomena.

The goal of the NASA Severe Storms and Local Weather Research Program is: "To aid the responsible storm forecasting agencies in improving the accuracy and timeliness of severe storms forecasts and warnings through research and development that combines aeronautical and space-related techniques and observations with other key indicators to severe storm development." This will be accomplished through the sponsorship of research and development activities to improve the basic understanding, instrument development, data interpretation, and forecast model development. To advance the knowledge of severe storms and local weather phenomena and ultimately improve our ability to forecast the phenomena requires detailed measurement of a host of parameters, wherein wind is a key parameter. It is through these observations that (1) theoretical models and concepts of severe storms and local weather phenomena are tested and (2) the intricacies and details of the phenomena are revealed for the theoretician and modeller to explain. In turn, these developments will improve the overall knowledge of the subject with an associated upgrading of our ability to forecast the onset, evolution, and dissipation of the phenomena.

The MSFC Airborne Doppler Lidar System is being developed to provide a capability of measuring the wind flow field at approximately 300 m intervals at a range out to approximately 10 km. Thus, in the airborne operating mode the Doppler Lidar System will have the capability of providing high-resolution wind measurements in cloud free air which can be used to construct detailed maps of flow with Nyquist wavelength of approximately 600 m, over an aerial extent dictated by the operating capabilities of the aircraft. Furthermore, it may also be possible to make inferences about the "intensity" of wind fluctuations with wavelengths less than approximately 300 m by examining the Doppler signal spreads. The Doppler Lidar data may also permit the construction of detailed maps of the spatial structure of turbulence "intensity" associated with severe storms and local weather phenomena. Thus, the MSFC Airborne Doppler Lidar System provides an exciting opportunity to perform important research on severe storms and local weather and thereby help accomplish the NASA Severe Storms and Local Weather Research Program objectives.

The exploratory meeting was initiated as a result of the interest created in part by (1) a recommendation by Dr. James C. Dodge of NASA Headquarters, (2) discussions at the 1979 MSFC Severe Storms Program Review, (3) a summary paper (Appendix A) by Mr. James Bilbro and Dr. William W. Vaughan concerning the application of wind fields associated with severe storms and local weather, (4) past successes of the MSFC Doppler Lidar team and other groups in remotely sensing aircraft trailing vortices, clear air turbulence, atmospheric boundary layer turbulence near the ground, low level mass divergence, chimney exhaust velocities, etc., and (5) NASA's desire to use space and aeronautical technology to explore the detailed structure of wind fields associated with severe storms and local weather.

The NASA has specific plans relative to application of the MSFC Airborne Doppler Lidar System; however, to assure that a well rounded scientific observation program is developed, the exploratory meeting was arranged. The objectives of the meeting were to (1) identify the major scientific issues associated with severe storms and local weather (especially those issues where the Doppler Lidar system could play a useful if not crucial role in acquiring the necessary data for improving our understanding and resolution), (2) identify data acquisition strategies that should be used to acquire data in the FY 1981 field test program (relative to utilization of the Doppler Lidar System and additional data sources/sets), (3) determine the scientific interests relative to applying the MSFC Doppler Lidar System to severe storm and local weather research, and (4) participation in the FY 1981 and subsequent field programs relative to planning, operations, and postflight data analysis. This meeting was an exploratory one because of the limitations of resources and time, however, NASA plans to sponsor a more extensive workshop in the future. Nevertheless, the meeting proved to be extremely fruitful. Many new and exciting applications of the MSFC Airborne Doppler Lidar System were identified.

Appendix **B** is the summary of a presentation made by James W. Bilbro **of** the MSFC Electronics and Control Laboratory and Michael C. Krause **of** the Raytheon Company, Wayland, Massachusetts. Appendices **C** and **D** include, respectively, the technical material presented by George **H.** Fichtl and John W. Kaufman **of** the MSFC Space Sciences Laboratory, on possible applications of the MSFC Doppler Lidar System, and a comparison by Gregory S. Wilson **of** Doppler Lidar System wind measurements with those made by the rawinsonde system. The agenda **for** the meeting and a list of the attendees are included in Appendices **E** and **F**, respectively.

III. DISCUSSION

Many of the fundamental questions related to severe storms and local weather remain unanswered. These questions were reviewed by the participants in light of the capabilities of the MSFC Airborne Doppler Lidar System. A list of research thrusts was developed to provide a basis for planning the FY 1981 field test program and development of the Doppler Lidar wind measurement technology. To a large extent, these fundamental issues remain unanswered as a result of our inability to make detailed measurements with the necessary resolution over a sufficiently large volume of the atmosphere near the same time. It appears that the MSFC Airborne Doppler Lidar System will be able to provide detailed wind observation that will significantly aid in the resolution or, at the least, provide clarification of many of these issues.

The discussion at the meeting encompassed various on-going applications and potential uses of the Doppler Lidar System to measure atmospheric quantities, especially wind velocity. In addition, comments were provided relative to other types of data that should be employed with the Lidar acquired data in order to obtain maximum scientific benefits from the Doppler Lidar data. This involved rawinsonde, aerosol, cloud physics, meteorological tower data, satellite cloud data, and various other conventionally measured data to aid in interpreting the remotely measured wind velocities as obtained by Doppler Lidar. A significant portion of the meeting was devoted to clarification of questions related to the operation of the Doppler Lidar and its capabilities to measure wind. Some of the facts mentioned which are important in planning a field test program and interpretation of the Doppler Lidar data involved the following topics.

1. Lidar backscatter energy as a function of aerosol concentration.
2. Use of chaff where natural aerosols are not present or are too low in concentration to provide satisfactory signal-to-noise ratio.
3. Effect of water droplets and ice crystals on range and back-scattered energy.
4. Measurement of aerosol concentration.
5. Data drop-out as a function of signal-to noise ratio.
6. Characterization of the Doppler Lidar spectrum.
7. Use of Doppler Lidar spectrum spread as a turbulence indicator.
8. Sources of errors and associated magnitudes, and preparation of a detailed system error analysis.

9. Effect of missing data points on postflight data analysis.
10. Pulsed **pair** data processing techniques.
11. Doppler Lidar operation relative to range gating and scanning.
12. Effect of aircraft motions on scanning and determination of precise location of wind measurement during postflight data analysis.
13. Determination of phenomena location for postflight data analysis.
14. Correlative ground truth and other comparative measurements to provide "**frame-of-reference**" on data from the Doppler Lidar System.
15. Flight paths to be employed in gathering thunderstorm data.
16. Airborne operation of Doppler Lidar with near vertical line of sight rather than horizontal line of sight, as is currently planned for the FY 1981 field program.

An insight to many of these topics was provided at the meeting. Some of these topics need further in-depth investigation, especially those related to the propagation of errors in the data. A detailed assessment of the error propagation and magnitudes will be provided. However, all participants agreed that a better knowledge of severe storms and local weather mechanisms could result from the application of the Doppler Lidar System in both airborne and ground-based modes of operation.

A. Primary Scientific Objectives

Based on the discussions that took place in the afternoon session of the meeting, the MSFC Airborne Doppler Lidar System has the potential of acquiring detailed wind field data applicable to a wide range of mesoscale flows with horizontal scales ranging from approximately 100 km to 0.5 km. The main areas in which the system appears to have the capability to provide a major opportunity for increasing our knowledge of mesoscale flows include convective phenomena, local circulation, atmospheric boundary layer, atmospheric dispersion, and industrial aerodynamics.

Several of the primary scientific questions and/or potential applications of the system within the first three of these areas were discussed in detail. They include:

1. Convective Phenomena:

- a. Determination of the detailed structure of thunderstorm cold **air** outflow above meteorological tower height.

- b. Measurement of detailed structure of warm air inflow required to maintain the thunderstorm.
- c. Determination of the structure of vorticity associated with severe storms via Airborne Doppler Lidar and Ground-Based Doppler Radar.
- d. Detailed structure of entrainment processes at the tops **and** along the sides of convective clouds.
- e. Detailed structure of flow in the cloud-free air at and above thunderstorm cloud base in terms of flow convergence and divergence and entrainment.
- f. Cumulus cloud flow dynamics measurement and model verification.
- g. Cumulus cloud turret entrainment processes observation in cloud-free regions.
- h. Measurement of "feeder" flow into base of cumulus clouds.
- i. Cumulonimbus cloud anvil structure.
- j. State of the atmospheric boundary layer during the severe storm life cycle (approximately 6 hours before thunderstorm formation to **a few** hours after). The central idea here is to clarify the role of the atmospheric boundary layer and how the severe storm and boundary layer are mutually influenced.

2. Local Circulations (Examples)

- a. Determination of detailed flow structure of land and sea breezes, and valley flows for scales of motion smaller than that associated with the primarily solenoidal circulation.
- b. Determination of detailed structure of flow over and around the terrain features such as mountains, hills, buttes, etc.
- c. Determination of detailed structure of flow associated with heat islands.

3. Waves and Turbulence

- a. Measurement of gravity wave structure, breaking waves.
- b. Measurement of generation and dissipation of clear **air** turbulence.
- c. Determination of mountain wave structure.

4. Atmospheric Boundary Layer Flows :

- a. Determination of flow characteristics at the "top" of the atmospheric boundary layer,
- b. Determination of mean flow variations due to surface inhomogeneities in the horizontal, i.e., change of roughness, heat capacity.
- c. Determination of mean flows above tower height.
- d. Determination of eddy structure in the horizontal, possibly leading to measurement of two-dimensional horizontal wave number spectra of atmospheric boundary layer flows.
- e. Measurement of eddy structure associated with Ekman layer instability.
- f. Acquisition of wind data as ground truth for verification of in situ and remote sensor designs; e.g., in the case of the latter, ground truth data for verification of wind fields derived from NOSS sea state data.

5. Aerosol Dynamics, Stratus and Cirrus Clouds:

- a. Transport of aerosols into bases, sides, and tops of clouds.
- b. Aerosol entrainment and entrainment processes associated with clouds.
- c. Aerosols into convective boundary layer.
- d. Aerosol flux through the tropopause and through other surfaces of discontinuity.
- e. Vertical structure of aerosols and "holes" in aerosol layers.
- f. Aerosol entrainment processes at top surface of marine strata.
- g. Cirrus cloud dynamics; e.g., particle distribution and middle-level natural cloud seeding by cirrus.
- h. Measurement of properties of thin cloud aerosol layers.

6. Engineering and Aeronautical Applications :

- a. Measurement of flow fields relative to wind energy conversion system siting, design, and design verification.
- b. Measurement of wind fields along takeoff and landing corridors of aircraft.

c. Measurement of **flow** over and about man-made structures for industrial aerodynamics applications.

d. Pollution monitoring and atmospheric dispersion model verification studies.

e. Agricultural seed, fertilizer, and pest control chemical dispersion studies.

B . Contributed Comments by Participants

The remainder of this section consists of brief commentaries by some of the participants in the meeting. The individual contributions remain essentially in the form furnished by the originators for inclusion in this report.

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AIRBORNE DOPPLER LIDAR WIND MEASURING SYSTEM:
APPLICATION TO ATMOSPHERIC PROBLEMS

The ability to map velocities over a large area on one side of the aircraft flight path offers a number of opportunities to elucidate scientific questions related to atmospheric dynamics. Several types of experiments are possible. One approach is to map the clear air flow field in the vicinity of cumulus cloud and seek to relate this to dynamic models of such flow. Using the echo intensity to map out aerosol concentrations we can consider experiments which seek to examine how cloud growth transports aerosol to higher altitudes when cloudy regions evaporate. Alternatively we can release aerosols as tracers to study transfers of air from one region to another.

At a higher degree of sophistication the very narrow lidar beam could be used with advantage in some circumstances to examine smaller scale phenomenon than the pulse length resolution would seem to allow. One such case is the entrainment phenomenon which occurs at the top of a cloud when dry air mixes into it. Because of the short penetration distance into the cloud itself, the return pulse will be averaged over a smaller distance at the interface than the pulse length and may consequently give information about structures less than 100 meters in scale. By flying the aircraft in a steeply banked turn above a growing cumulus cloud turret the entrainment could be studied in such cases.

Other circumstances are attractive from the scientific viewpoint. The earlier stages of cumulus growth are probably characterized by the initial turrets entraining sufficient dry air to completely evaporate some cloud tops, and these regions may well leave a detectable aerosol signature in the clear air surrounding growing turrets near cumulus cloud tops in the earlier development stages.

Entrainment is also known to occur at the top surface of marine stratus, and this could be examined by the same technique of flying the aircraft in banked turns, above the top of stratus decks.

The entrainment rate into the top of the clear air convective boundary layer is a matter of great current interest and releasing a line of aerosols just above such an inversion, and examining its entrainment, by flying parallel to the release at the same level, but a kilometer or so to the side, is an experiment which could fairly readily be tried.

These experiments relate to our need to better understand the process of turbulent entrainment through an interface separating to

regions of air, at an inversion or across a cloud surface for example. This is a fundamental aspect of all dynamic modeling of these conditions. The capability for documenting the feeder flow into the base of cumulus cloud is also an experimental opportunity of great importance in its own right and certainly should be exploited.

I personally would like to be involved in examining entrainment into the tops of growing cumulus turrets, *tis* an experiment likely to yield the quickest immediate pay off. However, some of the other cases might present opportunities which should not be neglected. If it proves possible to use a downward looking lidar beam at a later date I should be very interested in developing a close involvement in participating in its experimental use.

The use of the lidar to examine growing cumulus tops is appropriately associated with the CCOPC field experiments planned for the Miles City, Montana studies. To be effective a camera to photograph the center of the regions scanned by the lidar beam is a desirable supplement to the observational equipment.

The possibility of observing California Marine Stratus tops during tests of the system, or as targets of opportunity, may be worth considering, and I would certainly be very interested in such data.

Walter Frost
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POTENTIAL SCIENTIFIC RESEARCH WHICH WILL BENEFIT FROM AN
AIRBORNE DOPPLER LIDAR MEASUREMENT SYSTEM

There are many areas of scientific research which would greatly benefit from measurements of wind patterns in horizontal layers such as are potentially possible with the airborne Doppler lidar system. Many of these areas, particularly those relative to thunderstorm entrainment and/or convergence, have already been mentioned. In planning such measurements, however, one must be cognizant of the actual wind profiles which are measured by the current lidar system. That is, the wind distribution in the horizontal plane is measured. Therefore, regions of updraft and downdraft must be estimated from the flow field based on mass conservation laws. The option of banking the aircraft to obtain profiles in an oblique plane has possibilities but will probably require some careful evaluation before being effective.

Additionally, a major portion of carrying out a large-scale experiment, such as a study of the flow fields around thunderstorms, is the logistics required to coordinate the program with other agencies. It is essential, in my opinion, for thunderstorm modeling measurements to be coordinated with Doppler radar measurements from a ground-based station. The flow field in the nonprecipitous region measured by the lidar can then be coupled with the Doppler radar measurements in the precipitation region. The significant problem here is to assure coordination between the two measurements, i.e., radar measurements at the same scanning height as the airplane flight path, reasonable time coordination between both sets of measurements, position of the aircraft relative to the storm cell, etc.

Some areas of science which could benefit from measurement in the horizontal plane and which are immediately evident in the following.

Three-dimensional flow fields in the thunderstorm gust front. There are currently no reliable three-dimensional models of thunderstorm gust fronts which can be used in flight simulators or even to provide better understanding of the wind shear hazards to aviation operations. Scanning in the horizontal plane coupled with the currently available tower measurements would allow a simple three-dimensional model to be constructed. **More** beneficial, however, would be the application of the scanning lidar system in a vertical plane. Although it can be argued that vertical profiling is possible from a ground-based system, there are certain disadvantages to the ground-based results. It would be most advantageous to be able to scan the gust front to determine spatial

velocity distributions at specific instances of time. With a ground-based system one must wait for a storm to cross **over** the particular location of the measuring instrumentation. Moreover, to construct the spatial distribution one requires a more questionable application of Taylor's hypothesis than is necessary for the airborne acquired data. For the stationary measurements the assumption of Taylor's hypothesis under storm conditions may not be justified.

At the annual workshops on Meteorological and Environmental inputs to Aviation Systems, the need for wind and turbulence measurement along typical aircraft glide slopes under severe weather conditions has been identified as an urgent need to aviation safety. Measuring wind profiles during approach and takeoff could be readily carried out with the lidar system. This could be done as a special project where the aircraft flies specifically to gather the needed data **or** it could be boot-strapped on all other programs by simply turning the system on during takeoff and landing.

A triggering mechanism of tornadoes is suggested to be the vortices shed from the thermal updraft associated with thunderstorm cells. These vortices are similar to von Karman street vortices having their axis in the vertical direction. Such vortices, if they exist, could be effectively measured by scanning in the horizontal plane. The nature of the experiment in this case would be first to measure a sufficient number of wind distributions behind thunderstorms to verify if vortices indeed exist. Secondly, the strength of these vortices, if they exist, would have to be correlated with the characteristics of the storm. Sufficient pursuit of this theory might reveal new information on the triggering mechanisms of tornadoes and would thus enable long-range methods of detecting or forecasting tornadoes from measurements of other storm properties.

In addition to severe storms, the airborne Doppler lidar system offers particular promise in understanding the wind fields about terrain features. Evidence of vortex shedding by isolated islands in the ocean **or** by particular types of mountain features has been observed in cloud formations from satellites. These vortices must also exist in clear **air** conditions and can be ideally measured with the proposed Doppler lidar system. The understanding of vortex shedding by terrain features would provide new information relative to the climatology of areas downwind of the terrain features.

Finally, it is indicated in the January 1980 AMS News Letter that NASA is planning to become more involved with the Department of Energy in the wind energy program. One of the most pressing areas in terms of wind characteristics for wind turbine generator development is siting large wind energy conversion systems (WECS), particularly in complex terrain. It would appear that the Doppler lidar technique, particularly from the airborne platform, would provide a method for rapidly gathering information relative to regions of high wind potential over terrain features of an irregular nature. Large areas could be scanned on a periodic

basis, which would allow the development of a synoptic pattern of the wind fields in the particular area of interest. Thus the most promising sites for further detailed measurements can be quickly identified.

Other areas of interest relative to flow in complex terrain include valley flows. One proposed region for siting WECS is in the mouth of gorges off seacoasts. Flights at hilltop level along seacoasts could provide patterns of the flow convergence into the mouth of the various canyons, giving information on these canyons having the highest potential wind energy. Additionally, flow patterns associated with valley flows, mountain flows, sea breezes, and other such flow phenomena which cannot readily be measured with tower arrays or other conventional ground-based systems are areas of considerable scientific interest for which research could be supplemented with a tool such as the Doppler lidar airborne system.

Finally, in keeping with previous comments at this meeting, there is a strong need to carry out a detailed error analysis of the proposed system in sufficient depth to provide knowledge of the accuracy which can be achieved with this measurement tool. Such information is essential to the scientist or meteorologist planning an experimental program. Although the accuracy of the Doppler lidar in terms of pulse frequency, spectrum analysis, etc. , is well documented, there are large uncertainties associated with the Doppler lidar deployed from an airborne platform which must be studied. The influence of time lag in terms of characteristic times of the storm motion; typical roll, yaw and pitch effects encountered while flying close to typical storm activity, and other such sources of error must be carefully analyzed.

There are obviously many areas of research which can be significantly aided by the Doppler lidar airborne system. A systematic development of the airborne Doppler lidar will thus provide a strong tool for atmospheric wind measurements. Additionally, the technology development associated with this systematic development of the current system will have direct application to satellite systems for which the lidar also promises to be an effective instrument for atmospheric research.

James R. Scoggins
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Summarized below are some of my thoughts about the system and its potential uses.

1. **Error analysis.** A comprehensive error analysis of the system is needed with the ultimate objective of specifying the accuracy and representativeness of the wind data obtained from the system. This study will not be easy and will involve the influence of all errors upon the final product, singly and in combination. Some errors will be independent of all others and some will not. The methods used to propagate errors through the system and to determine their impact and influence upon the final product will be very difficult yet indispensable in terms of confidence in the data as well as its utilization.

2. **Design of field program.** The design of the first major field season using the Doppler Lidar should be done in such a way as to insure the greatest probability of success. This will of necessity be coupled to the error analysis, operational problems of the equipment, limitations of the equipment, and the nature of the scientific problem being addressed. Let me give one example to illustrate what I mean. Entrainment is an intriguing and important aspect of thunderstorm growth and development and is a problem that has been unsolved for many years. The effects of entrainment on internal cloud properties can only be measured inside the cloud, after ambient air has been mixed with cloud air. The Doppler Lidar cannot measure effects inside a cloud and, therefore, it is a rather indirect approach to attempt to draw definitive conclusions about entrainment if one only has environmental winds to consider. This is not to say, however, that the Doppler Lidar data will not contribute to the solution of the problem by the direct study of entrainment at the interface between clouds and clear air.

For optimum use, however, it may have to be used in conjunction with other measurements rather than being the principal tool. On the other hand, a problem for which the Doppler Lidar may be the principal source of data would be a mapping of the flow field around a thunderstorm. It seems that it may be possible to map the horizontal inflow into a thunderstorm perhaps at two or three levels. This inflow could also be determined from independent rawinsonde and other data, and if similar results are obtained would demonstrate beyond doubt the utility of the Doppler Lidar. This would give confidence in the data which would form a basis for its further utilization.

3. I list here a number of potential areas most of which were discussed at the meeting.

a. **Convective activity.** This could involve a study of the outflow region from the storm, mechanisms of new storm development or

storm intensification, the production and concentration of vorticity within the storm (G. H. Fichtl discussed this as an idea), and a number of other topics which we discussed at the meeting.

b. Land and sea breezes and other local breezes. The Doppler Lidar could be used to determine the extent and magnitude of these breezes, and their diurnal variability.

c. Studies of the low level vertical wind profile.

d. Clear **air** turbulence.

e. Pollution monitoring especially from stacks and other rather confined sources.

f. Determination of vertical motion especially in the vicinity of thunderstorms or in regions where thunderstorm development is anticipated.

g. Mixing near cloud boundaries.

h. Flux through internal boundaries. This topic was not mentioned at the meeting but could be important in determining mass transport through the tropopause, frontal zones, or surface inversions.

i. Determination of waves on internal zones of discontinuity. This topic was not discussed by the Doppler Lidar would be ideally suited for studying these waves.

4. Verification of Doppler Lidar data by independent measurements. It is essential in order to develop confidence in the data and to verify the accuracy and representativeness of the data determined by an in-depth error analysis that the data be verified by independent measurements. This could include wind profiles, wind measurements made at a point by anemometers, chaff, or some other tracer, evaluation of the spectral broadening as function of the properties of turbulence, and a comparison of data from independent measurements during each and every field program.

In my opinion, items 1 and 4 should progress continuously from now until the first held program is conducted. Moreover, the first major field program in which the Doppler Lidar is used should be a **program** in which there are observations from numerous sources that could be used to verify the Doppler Lidar data as well as using all sources of data jointly to address a given problem. The error analysis and verification and validation of the data cannot proceed at a rate that is too fast.

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Discussions at the Marshall Space Flight Center indicate that the NASA personnel have well thought-out the potential applications of the Doppler Lidar measurements. I will join those who have stated that the wind fields derived from this technique have the potential for great **value** in determining the material (e.g. water vapor) and energy budgets, momentum transports, etc., in the environment at all stages, including the pre-condensation stage, in the development of convective clouds. If this potential can be reached, extremely valuable data -- data that has been sought for decades -- will become available.

This complete three-dimensional depiction of the winds with desirable space and time resolution seems to be in the distance. Even *so*, a field of planar wind vectors will be of great value in describing the convective cloud environment and I do not believe I need to elaborate on this capability. However, I will join the recommendation that the accuracy and resolution of the technique be carefully established. Instrumented towers in the San Francisco and Boulder area may be of value for this purpose -- particularly in the check-out phase. I also join those who emphasize the necessity to know the location and characteristics of clouds that may influence the wind field. One should know the stage in development of these clouds and ideally, the evolution with time of clouds so the wind fields can be correlated with dynamic vigor and stage in development. Note, radar would be useful in this regard, but ordinary photog-raphy might be of more importance; for one would be interested in the location of cloud edges and a general description of the cloud rather than a description of the presence or absence of large hydrometeors. It should go without explicit statement that the value of the Lidar measurements for convective cloud studies would reach its potential only if simultaneous measurements using other sensors are made -- in other words, the measurements are made in the context of a larger program.

Since the Lidar uses a wave length in a water absorption band, it would be most desirable to know the attenuation of the signal as a function of the water vapor as well as aerosol content of the atmosphere. I suppose theory would be adequate in this respect. One also should have measurements of water vapor content, in the field where measurements are being taken. I would plan to carry an instrument for this purpose. It would seem to be a relatively small addition to the cost of the program and would provide a means for additional quantitative evaluation. An independent measurement of aerosol properties would also be valuable, but perhaps this would be too ambitious. In thinking about applications of the Lidar, I continually return to the value of being able to determine the properties of the aerosol that are serving as the Lidar targets and believe interesting and valuable information would become

available if one could extract properties of the aerosol from the Lidar measurements. Presumably, one needs to account for water vapor attenuation. Among other things one could look for are vertical stratification in aerosols, "holes" in aerosol layers (perhaps due to entraining downdraft shafts), properties of thin clouds (considered as the aerosol causing the scattering), stratosphere, troposphere transport of aerosols, etc.

Incidentally, a study involving cirrus clouds to learn their dynamics (using the Doppler technique) and their particle distribution as a function of time and space would be of great interest. The scientific motivation for acquiring these measurements is the role of cirrus in seeding clouds in cyclonic storm (i.e., creating precipitation bands). (Cirrus characterization even in the absence of lower clouds would be relevant to this topic.)

Such a study would also make use of the high latitude capability of the 990 - a capability that few cloud physics research aircraft enjoy and consequently one would be plowing essentially new fields. This leads to the comment that the high latitude capability of the aircraft should be exploited, whenever possible.

At the meeting, I mentioned the possibility of using a volatile hygroscopic material (such as fuming sulfuric acid - but something else would be better) to act as the scattering particles in the absence of sufficient natural aerosol. (Helmut Weickmann would be a valuable contact if this were to be pursued.)

I recommend that careful attention be given to possible targets of opportunity that would provide useful scientific data during the check-out phase of the aircraft installation. The cirrus cloud study mentioned above is a possible candidate; airflow associated with topography is another - the San Francisco area provides a rich diversity in topography ranging from the simple to the complex.

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I. Purpose of Measurements

A. "Calibration"/Intercomparison

1. Fly at constant altitude in an aerosol-laden constant wind. Relate angle of crossing wind to output from Lidar Doppler, particularly flying into and with the wind. Possible conditions - nighttime, in polluted **air** which had been included in daytime boundary layer, but is part of free **air** stream at night.

2. Tower flyby's - both single and array tower anemometers NOAA Boulder, also somewhere on west coast (San Francisco?).

B. "Credibility"

1. Comparison with accepted airborne systems, such as rawinsondes.

C. Hard Science

D. Exploratory Science (G. H. Fichtl called this akin to studying fluid dynamics by playing in the bathtub, but I feel that a judicious choice of exploratory science objectives has the potential of large returns in scientific insight.)

II. Physical Phenomena under Investigation

A. Phenomena Associated with Water Clouds

1. Sub-cloud measurements (note - it was stated that this region has the high aerosol concentrations needed for good signal return).

- a. Storm life cycle of boundary layer convergence.
- b. Mass flux and precipitation efficiency.
- c. Thermal cell interactions.
- d. Aerosol particle flux into cloud base.
- e. Gust front structure.

"Universities Space Research Association Visiting Scientist.

2. Cloud flanks [note – Jay (someone) cautioned that aerosol concentrations may well be below signal threshold limits in this region.] I feel that two factors can make measurements in this region possible – first, cloud development in a layer occupied by dissipating turrets from earlier cell development. Dissipating clouds will tend to leave behind aerosol residues. Second, detrainment of aerosol at portions of the cloud flanks will also tend to supply aerosols.

a. Wind fields, gust fronts, large-scale entrainment.

b. Small-scale turbulence, entrainment, aerosol flux, detrainment (seed aerosol-free air with chaff or fuming sulfuric acid-Telford, DRI).

3. Cloud top-note-similar concerns apply here as to measurements near cloud flanks.

a. Entrainment and detrainment.

b. Turret growth and development.

III. Execution of Experiment

A. Error analysis – thorough error analysis needed before field phase and as soon as possible in test planning phase.

1. Effects of pulse length, integration time, aircraft speed, aircraft orientation, frequency stability, scanner stability, etc.

B. Data acquisition and handling – considerable dismay was expressed that full details on the turbulence spectrum would not be kept in permanent storage for post-flight analysis.

C. Scanning mode – considerable interest was evident for alternate modes of scanning, particularly upward or downward looking scanning. Capability of system for conical scanning, aircraft – orientation – compensated scanning, and aircraft wing up scanning was presented. It was understood that major modifications to the aircraft would be required for a downward looking scanner, resulting in large cost and logistics impacts. Nevertheless, interest was strong for the potential of such a system. Concern was expressed for the sensitivity and response time of scanner compensation for aircraft motions.

D. Flight plans – it was recognized that consideration of flight plans was premature, except for interest in aircraft wing up flight as a temporary substitute for downward-looking scanning. Some potential flight plans were presented – cloud circumnavigations, frontal traversals and parallels, and spiral cloud circumnavigations. Capability of aircraft for very low altitude flight (~400 ft?) was presented, consideration of aircraft staging was discussed, including 6-hour duty cycle – fuel

limited, and need for a large airport facility, including Air Force Bases. Because of limited available flight hours, a carefully prioritized list of scientific objectives needs to be established for the Lidar System. Case studies were suggested as preferable to large statistical samples.

IV. Personal Interest

The capability of the LDV to acquire three types of information, signal intensity (related to aerosol concentration), signal offset (related to velocity), and signal width (related to turbulence) can be used to great advantage in a certain area of aerosol and cloud microphysics. An aerosol-laden region is typically separated from the surrounding clear air by a turbulent interfacial region. The structure of this interfacial region (billows, cusps, etc.) and the aerosol fluxes across it are of great interest in understanding and modelling a wide variety of aerosol source and aerosol life-cycle problems.

The LDV information on velocity and concentration can be used to give both an average interfacial aerosol flux and, perhaps, a detailed look at the aerosol entrainment and detrainment mechanisms. For example, it is conceivable that information could be directly obtained on whether turbulent entrainment is isotropic, as has been tacitly assumed, or non-homogeneous, as recent thought is suggesting. In addition, the turbulent intensity associated with the entrainment/detrainment would be useful to know for modelling purposes. An additional feature of the LDV which can be used to advantage is that the signal drops out when there is no aerosol. Thus the edge of a cloud should be discernible by a rather rapid increase in signal intensity, followed by significant, perhaps rapid, attenuation as the pulse enters the cloud. In addition, regions of the cloud which are detraining aerosol, or dissipating, should be discernible. Rapid measurements of detrainment fluxes should then be possible.

The significant difference between my interest and those of most others expressed at the review is that for my purposes, the determination of aerosol concentrations is the prime measurement, whereas for most others, aerosol particles serve merely as a tracer for the atmospheric wind field.

A summary of the types of physical phenomena for which the measurements described above would be of considerable interest is given on the next page. Note the potential in many of these systems for satellite remote observations.

V. Measurements of Aerosol near Turbulent Interfaces from Aerosol Sources

A. Horizontal - Stratiform Aerosol Systems

1. Fair-weather boundary layer (Haze)

- a. Surface structure - cusps, clouds, gravity waves, rolls.

b. Understructures – thermal plumes (aerosol sources for boundary layer?) convective rolls.

c. Desirable to have downward looking beam, either direct or by tilting plane. Possible, however, to fly level, right at boundary layer top. If downward looking, desirable to scan transverse to aircraft line of flight. If side-looking, desirable to scan up and down or conical.

2. Fog and Stratus

a. Surface structures, cusps, turbulence, entrainment, detrainment, dissipation.

b. Downward looking beam required, scanning transverse to aircraft path.

3. Cirrus – both pre-frontal, thunderstorm anvil, and frontal-cloud generating cells

a. Convective activity, especially in generating cells.

b. Detrainment from pre-frontal and anvil cirrus.

c. Turbulence from anvil cirrus, collapse of severe storm tops (tornado prediction?).

d. Downward looking required for generating cells, side-looking ok for others.

B. Local or Area Sources

1. Water Clouds

a. Lee wave cloud dynamics.

b. Cloud flanks and tops of small cumulus, cumulonimbus. hurricane, ITCZ

2. Non-Water Clouds

a. Urban/Industrial/Agricultural Aerosol Sources.

b. Volcanoes.

c. Dust Storms, Dust Devils.

d. Saharan dust layers.

Note that in some cases, a fixed or traveling surface based LDV can be used, and has been, to study the phenomena. However, an airborne LDV has the advantage of speed, for higher areal coverage and less dependence on assumptions of stationarity. Moreover, several of the other systems are almost completely inaccessible to ground-based LDV's.

The scanning capability of the MSFC LDV, if it can be also incorporated into a ground-based system, gives the flexibility to choose between ground-based and airborne observation, depending on the physical system involved, the scale of the system, and the resolution required. For example, it is possible that the boundary layer structure could be better investigated with a traveling ground-based LDV, using a scanner inclined from the vertical, and scanning up and down around that angle.

NOTE: Some of these objectives would require higher data acquisition rates to achieve the desired resolution in a quasi-3-dimensional scan area.

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The MSFC Doppler Lidar System is potentially a very powerful measurement system. Below are comments and ideas about the system and the research program that were not covered by someone else at the meeting:

1. **Error analysis** - Since this system is unique, it will not be possible to verify the results exactly. The emphasis at first therefore should be on those measurements for which there is a measure of insitu "ground truth" or comparisons with other remote instruments. Even so, confidence in the system and the data obtained will depend on the error analysis that is done by Bilbro, et al. Accordingly, the error analysis should be carefully done and should be easily understood by meteorologists.

2. **Agricultural burning in California central valley** - There is currently a big controversy on this subject so any measurement of the overall circulation patterns of the central valley, or details of the flows around the large smoke plumes would be of considerable interest. There are plenty of aerosols any time in the central valley and especially so during the burning season (early spring and late fall). People at University of California Davis have done work on this topic and would be helpful. It is quite close to NASA Ames and would be ideal for testing the system.

3. **Air-Sea interaction** -- At the meeting, no one mentioned the oceanographic possibilities of the Laser Doppler system. There are numerous possible applications. One that would be ideal for comparison between two remote instruments is to compare with the NOSS sea state radar system. It is a system being developed for the big NOSS satellite that uses radar to look at the ocean wave spectrum and deduce the wind direction and speed. The experiment would be to fly the NOSS instrument as high as possible (U2?) and the Laser Doppler as low as possible and compare the results. Evidently there are some ambiguities in the wind direction determined by the NOSS system, so there are real possibilities for some useful contribution to that program, along with scientific results from looking at air-sea interaction. This would also make this system more interesting to the people who are interested in the eventual satellite application of the laser Doppler. Two more oceanographic possibilities come to mind. There are two big ship programs in the summer of 1981: one is in the Gulf of Alaska (STREX) and another in the tropical Pacific (Dennis Moore, University of Hawaii). Both would offer lots of possibilities for ground truth as well as making a contribution.

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As now worked out, the Doppler Lidar can be flown on the Convair 990 which is committed to about 60 hours for observations for the Atmospheric Sciences Division. They may fly out of either Socorro, New Mexico, or Miles City, Montana, during the CCOPE* project. They expect to be in Miles City from mid-June through July of 1981. They hope that 20 hours will be all that is needed for testing the equipment which would leave 40 hours for experiments.

It appears that the major scientific issues that could be treated by the Doppler Lidar would be (1) the question of precipitation efficiency in a storm in which the Lidar would be just one part of the whole measuring system needed to find the precipitation efficiency, (2) studies of general entrainment into the sides and tops of clouds, and through the top of inversion layers, and (3) gust front initiation and evolution.

Our modeling group is concerned with many of these topics and has done work in mesoscale convergence effects on cloud growth, cell interactions, gust front formation and evolution and the development of the convective boundary layer. We would be interested in being involved in such studies in association with the Lidar Doppler.

It appears to us that the preferred way of conducting experiments would be through horizontal soundings made by the aircraft, most often the aircraft would be flown near cloud base and the lower elevations where aerosols exist, but some studies up in the anvil would be extremely interesting. Some areas of the country have outstanding mammatus formations in cumulonimbus clouds and to measure the detail of the motion in such situations could be very interesting. In addition, the anvil outflow is very important for mass budget studies of the storms. Studies of the anvil could be checked versus the satellite measurements of the same clouds to check the accuracy of the satellites and the Lidar Doppler or at least to check the consistency of the two measuring systems.

*Cooperative Convective Precipitation Experiment

Joanne Simpson
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Although I know little about the workings of that instrument and its range of validity, I believe the need to measure air velocities in the clear around, above, and under convective clouds is one of the most urgent in cloud and severe storms research and forecasting and of major importance to understanding the impacts of cloud systems on larger scale flow patterns.

In the April issue of the Journal of Applied Meteorology* I have an article specifically quoting your Bulletin article in this regard.

*Bilbro, James W. and William W. Vaughan, 1978 "Wind Field Measurement in the Nonprecipitous Regions Surrounding Severe Storms by an Airborne Pulsed Doppler Lidar System," Bulletin of the American Meteorological Society, Vol. 59, No. 9, September 1978.

IV. SUMMARY REMARKS

There appears to be a consensus that the presently configured MSFC Airborne Doppler Lidar System has the capability of acquiring detailed wind field data which would give the atmospheric scientist new and needed insight into micro- and mesoscale flows. The range of phenomena that could be explored with the system is broad and includes convective flows, local circulations, atmospheric boundary layer flows, entrainment, atmospheric dispersion, industrial aerodynamics, and others. The Doppler Lidar system provides an opportunity to acquire detailed wind field data which could give us a "new look" at these phenomena and aid in the clarification and possible resolution of fundamental scientific questions which, if resolved, would lead to significant new scientific understanding. In light of the current plans for the FY 1981 test program and the potential for research and data analysis opportunities in FY 1981 and FY 1982, the meeting produced the following viewpoints and conclusions:

1. In developing the FY 1981 test program plans for the Doppler Lidar every effort should be made to coordinate tests with other measurement programs so as to obtain a sufficiently large "ground truth" data base for postflight evaluation of the Doppler Lidar System. This additional data base could provide unique opportunities to study certain micro- and mesoscale flows at a level of observational sophistication not possible in the past.

2. Participation of the Doppler Lidar System in the Cooperative Convective Precipitation Experiment (CCOPE) could result in unique data sets which could be used for system verification and at the same time significantly contribute to CCOPE scientific objectives.

3. A comprehensive error analysis of the system which specifies the accuracy of the system and representativeness of the wind data is needed. (NOTE: An error analysis is available and will be presented at the June 1980 Severe Storms and Local Weather Program to be held at the NASA Marshall Space Flight Center.)

4. Significant scientific benefits can be obtained by operating the Doppler Lidar in orientations other than that currently planned for in the FY 1981 flight test program. For example, orienting the Doppler Lidar with a vertical line-of-sight could be used to acquire fundamental new data on entrainment phenomena that occur at the top of a cloud when dry air mixes into it.

5. A systematic development of the airborne Doppler Lidar will provide a strong tool for atmospheric wind measurement. The technology associated with this systematic development of the current system will have direct application to satellite systems for which the Lidar also promises to be an effective instrument for atmospheric research.

6. During the acquisition of measurements of flows associated with phenomena characterized by clouds, it will be necessary to acquire additional data which can be used to determine the location and characteristics of the clouds, stage of development of these clouds, and, possibly, the evolution with time of clouds so that wind fields can be correlated with the dynamic intensity and stage in development.

7. Every effort should be made to include instrumentation in the **FY 1981** test program to acquire independent measurements of water vapor content and aerosol properties in the field where measurements are to be taken. These data would be used in postflight data analyses to assess signal attenuation as a result of water vapor absorption and scattering by the aerosols.

8. The full impact of the Airborne Doppler Lidar System on the atmospheric sciences will not be realized unless the data (Doppler Lidar and supporting data sets) from the FY 1981 and subsequent year test programs are systematically analyzed by the scientific community. Accordingly, it is in the best interest of NASA to provide adequate support for the scientific and engineering analysis of these data and the assessment of scientific requirements for follow-on development of the Doppler Lidar system as it evolves from the present airborne configuration toward an airborne instrument.

APPENDIX A

WIND FIELD MEASUREMENT IN THE NONPRECIPITOUS REGIONS SURROUNDING SEVERE STORMS BY AN AIRBORNE PULSED DOPPLER LIDAR SYSTEM*

James W. Bilbro and William W. Vaughan

Abstract

Coherent Doppler lidar appears to hold great promise in contributing to the basic store of knowledge concerning flow field characteristics in the nonprecipitous regions surrounding severe storms. The Doppler lidar, through its ability to measure clear air returns, augments the conventional Doppler radar system, which is most useful in the precipitous regions of the storm.

A brief description of the Doppler lidar severe storm measurement system is provided along with the technique to be used in performing the flow field measurements. The application of the lidar is addressed, and the planned measurement program is outlined.

1. Introduction

The dynamic behavior of the atmosphere in and around storms is well known to airplane crews and passengers who have encountered severe turbulence and to individuals in every state who have had the misfortune to experience the devastation of tornadoes and hurricanes. In an effort to understand the factors responsible for the development and growth of thunderstorms, and especially severe tornado-producing storms, considerable research has been devoted to the development of measurement systems and the acquisition and analysis of data (NAS, 1977). Even so, we still do not know why a seemingly select few of the multitude of clouds we see in the sky suddenly develop into towering cumuli and why yet another more select group become tornado-producing thunderstorms.

Research during the past three decades (i.e., Byers and Braham, 1949; Miller, 1959; Fujita, 1974) has made notable contributions to our current understanding of thunderstorms and their development. The capability of the Doppler radar to penetrate and measure the interior dynamics of a thunderstorm has revealed important data on circulation patterns, cell development, and rotational behavior (Lemon et al., 1977). Atmospheric flow structures, especially the microscale and mesoscale, in the clear air near the thunderstorm have yet to be adequately measured and studied in relation to the development and growth of thunderstorms. In recent years, considerable progress has been made in the field of coherent Doppler lidar (Weaver et al., 1976). It is now well within the

* Bulletin of the American Meteorological Society, Vol. 59, No. 9, September 1978, pp. 1095-1100.

technology to have a pulsed Doppler lidar mounted in an aircraft that will provide a map of the two dimensional wind fields as the aircraft surveys the nonprecipitous regions surrounding a storm (Fig. 1). Combining this system with an airborne Doppler radar could provide the capability to map the wind flow field in and around an existing or developing storm. Some of the fruitful areas of investigation that will be opened by an operational airborne Doppler lidar system include research into (1) interaction of the ambient wind field and the storm, (2) entrainment, (3) outflow bursts, (4) wind field circulation and dynamics, (5) relationship of the wind field with synoptic or subsynoptic wind flow measurements from standard rawinsonde systems, and (6) identification of unique storm associated wind field characteristics,

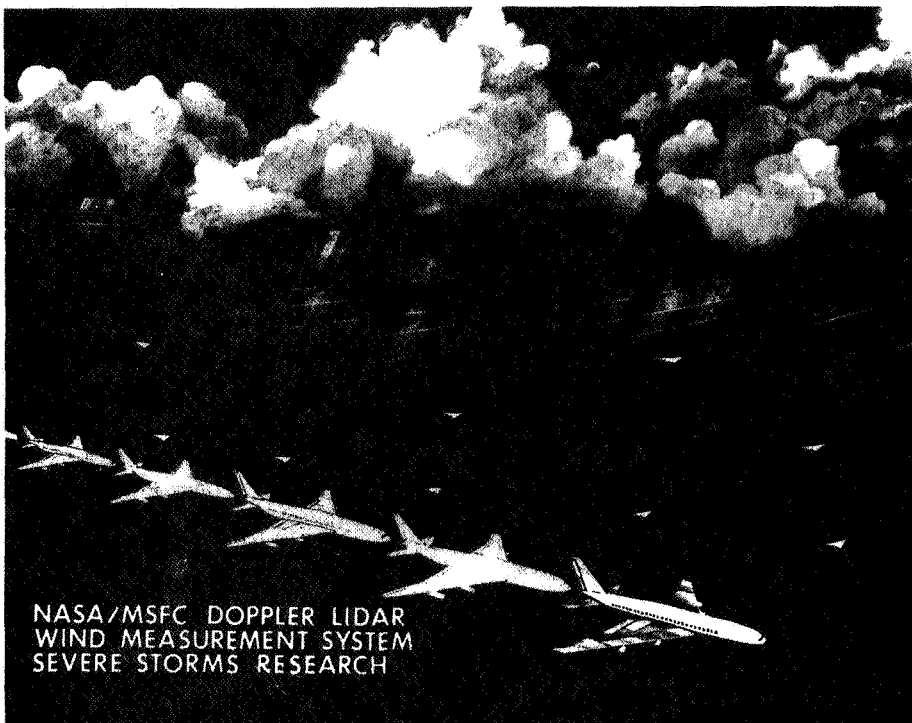


Figure A 1 Doppler lidar flow field mapping

It is evident that additional knowledge of severe storm processes is of considerable importance from both a scientific and an applied viewpoint. Since the understanding and subsequent characterization of these events directly influence our day to day activities, NASA has initiated a severe storms program directed toward aiding the responsible agencies in improving the accuracy and timeliness of severe storm forecasts and warnings. This is to be accomplished through a research and development effort that combines aeronautical and space related techniques and observations with other key indicators of severe storm development. The program will enable the development of better satellite remote sensors

and provide a better understanding of the potential of current sensor systems.

Under the sponsorship of NASA's Office of Space and Terrestrial Applications, the George C. Marshall Space Flight Center is currently applying available technology toward developing a pulsed CO₂ Doppler lidar for use in severe storms research. The system will permit velocity flow field mapping in the nonprecipitous regions surrounding severe storms. Preliminary studies on the concept (Thomson et al., 1976) and the hardware design (Raytheon, 1977) have been completed. Preparations are underway to modify NASA's Marshall Space Flight Center's pulsed Doppler clear air turbulence (CAT) detection system (Jelalian et al., 1972) to perform measurements of the wind field in the regions surrounding severe storms. This paper will describe the pulsed Doppler lidar system as applied to severe storms research. The lidar is expected to be ready for operation at the time the new high-resolution satellite sensor system, VISSR (Visible and Infrared Spin-Scan Radiometer) Atmospheric Sounder (VAS), is scheduled for geosynchronous orbit in late 1980 or early 1981 (Allison et al., 1977).

2. System Description

Successful application of a coherent Doppler lidar to obtain atmospheric flow field information relies upon scatterers being entrained within the atmosphere. At the 10.6 μm wavelength of CO₂ radiation, the primary scatterers are naturally entrained particulate matter such as dust and pollen. These particles tend to follow the motion of the atmosphere in which they are entrained, and therefore measurement of the velocity of these particles provides a reliable measure of the velocity of the ambient wind field.

Measurement of the particle velocities by coherent Doppler lidar is possible because of two primary factors: (1) the circular, polarized transmitted laser beam is rotated 180° in polarization when backscattered along the axis of illumination by particles within the beam path, and (2) the return (backscattered) beam is Doppler shifted in frequency by an amount determined by the direction and rate of travel of the particle. The coherent detection of the return beam and the subsequent spectral analysis of the resultant electrical signal provide the vector component of the particle velocity parallel to the line of sight of the transmitted beam.

The pulsed Doppler lidar to be used in this measurement program is a modification of the system developed for CAT detection. A simplified block diagram of the modified system is shown in Figure 2. To achieve a basic understanding of the lidar, it will be helpful to follow the path of a signal as it travels through the system from the master oscillator laser to the displayed data. In the operation of the system a small portion of the output energy of the master oscillator laser (1) is picked off for use

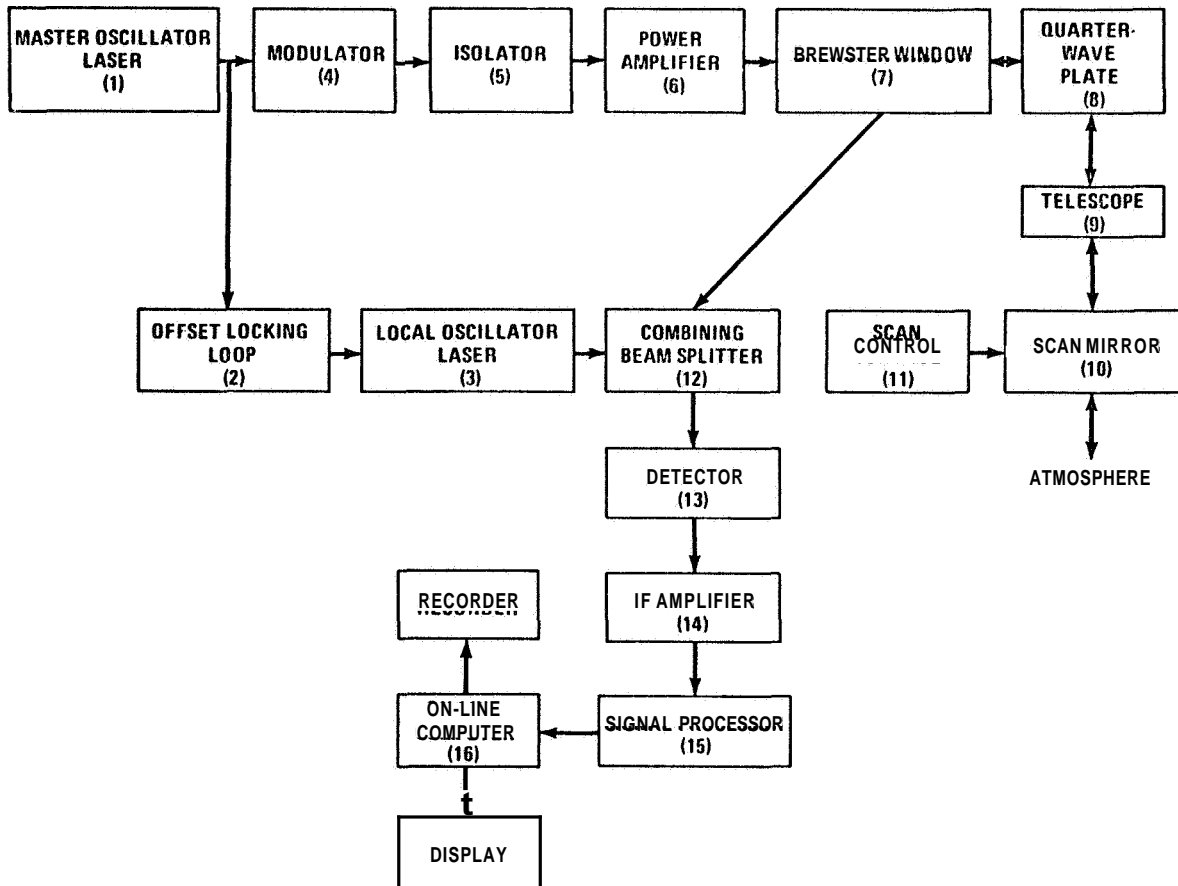


Figure A-2. Simplified Doppler lidar system block diagram.

in an offset locking loop (2) that maintains the local oscillator laser (3) at a constant offset frequency from the master laser. The main portion of the continuous wave output of the master oscillator laser is directed to an electro-optic modulator (4) that amplitude modulates the horizontally polarized beam to form a pulse train. The pulse train then passes through an optical isolator (5), designed to reduce backscatter from the telescope, and into a power amplifier (6). Upon leaving the power amplifier, the pulse train passes through a Brewster window (7) aligned for horizontal polarization, through a quarter-wave plate (8) to rotate the polarization to circular, and into a modified Cassegrainian telescope (9). The telescope collimates the pulsed beam and transmits it to the atmosphere with the aid of a scanning mirror (10). The scanning mirror control system (11), along with the range gate, determines the region of space to be sampled. The return beam, Doppler shifted and rotated in polarization, comes back along the same path into the telescope (9) and through the quarter wave plate (8). Because of the reverse polarization of the return beam, the pulses upon passing through the quarter-wave

plate, now become vertically polarized. These pulses are then reflected by the Brewster window (7) to a beam splitter (12), where they are combined with the local oscillator beam and transmitted to the detector (13). The coherent mixing (heterodyning) of the two beams results in an interference pattern being imaged on the surface of the detector. The interference pattern fluctuates according to the difference in frequency of the two beams, thereby resulting in an electrical signal out of the detector in the form of a frequency-modulated wave with the modulation frequency being equal to the Doppler shift of the return beam. The magnitude of the Doppler shift is given according to the relation $\Delta f = 2V_r/\lambda$, where Δf is the Doppler shift, λ is the wavelength of the laser source, and V_r is the radial velocity. At this point, the signal from the detector is sent through an IF amplifier (14) to the signal processor (15). The signal processor calculates the power spectral density of the pulse return for each range interval (gate) from the minimum to the maximum ranges of interest. The processor then extracts the spectral mean and standard deviation for each range gate and formats the data for transmission to an on-line computer (16) for additional processing. The computer receives spectral and range information from the processor, scan position information from the scanner, and aircraft position information from the inertial navigation system. Storm location relative to the aircraft will be provided either through the on-board radar system or in conjunction with a ground-based tracking system.

The characteristics envisioned for the system now under development are as follows:

Wavelength: 10.6 μm .

Pulse width: 1 μs .

Peak power: 5 kW.

Pulse repetition: 200 Hz.

Beam width: 30.54 cm.

Horizontal range coverage (perpendicular to flight path): $\sim \frac{1}{2}$ - 10 km.

Data point resolution: ~ 150 m.

Vector component measurement: up to 40 m/s.

Vector component threshold: ~ 1 m/s.

3. Measurement Technique

The primary form of the data output of the system as presently envisioned is that of a high-resolution, two-dimensional map of the flow field in the area surrounding the storm. This map would be a plot of the vector velocity components that lie within a horizontal plane determined by the flight path of the aircraft. Although the initial effort will be confined to the collection of two-dimensional data, a series of passes

by the aircraft at different altitudes would lead to an improved three-dimensional picture of the flow field. The feasibility of such a measurement would depend a great deal on the extent and stability of the storm.

Since the Doppler lidar is inherently a line-of-sight measuring device, scan techniques must be employed to obtain the vector components required for the flow field map. These scan techniques must allow for at least two independent observations of each point of interest. The angle between observations must be sufficient to accurately resolve the components, and the time between observations must be short enough to provide a meaningful representation of the mean flow.

A "two-point" scan technique has been employed in generating the pattern shown in Figure 3. This pattern is generated by first directing the beam to an angle forward of the normal to the flight path and within a horizontal plane at the altitude of the aircraft for a number of pulses and collecting data from the various range intervals. The beam is then directed to a line of sight to the rear of the normal, still keeping within the horizontal plane, and again collecting data for a number of pulses and range intervals. As this process is repeated, it is evident that a rearward-looking scan will at some time intersect one or more forward-looking scans generated previously. The resulting pattern in space, as indicated by Figure 3, is a grid in which the crossing points represent regions where vector velocity components are obtained.

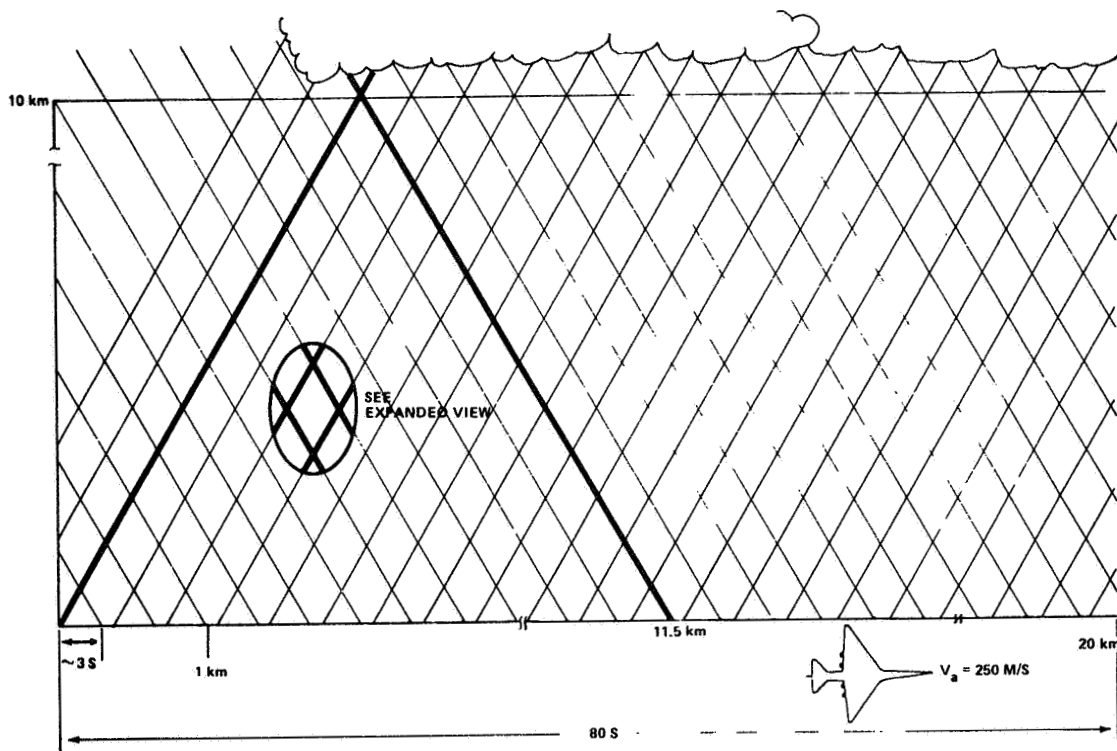


Figure A-3. Doppler lidar flow field scan pattern.
(Expanded view is in Figure 4.)

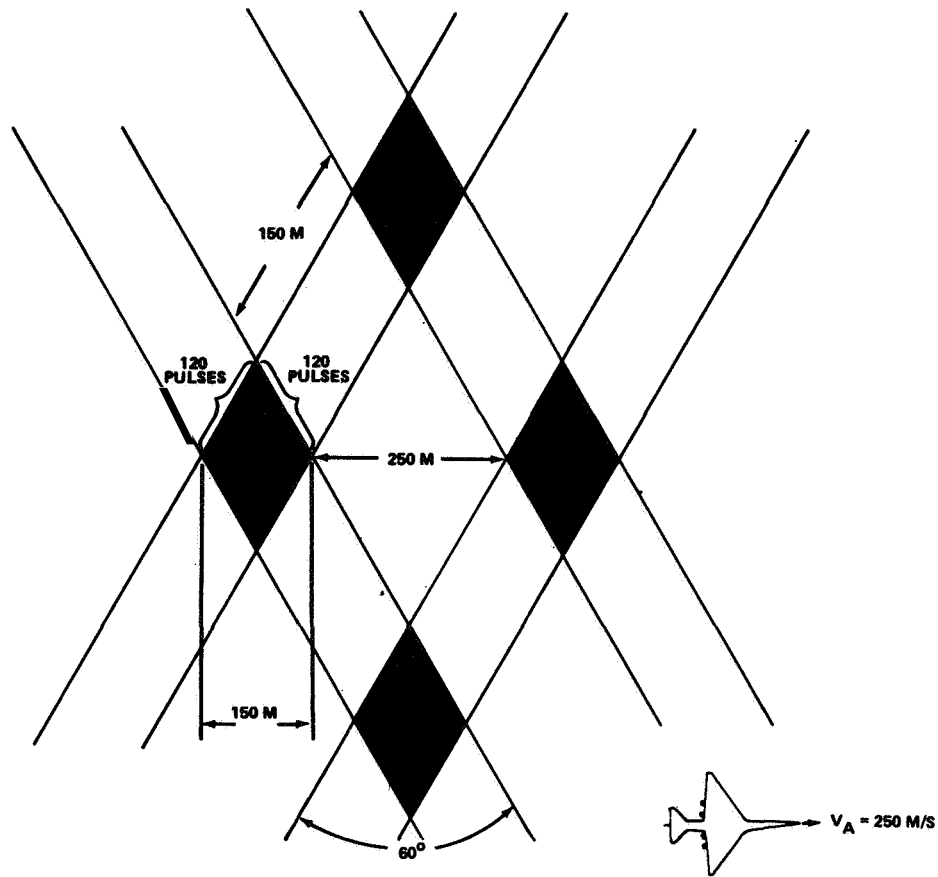


Figure A-4. Expanded view of scan pattern.

The formation of a grid point is shown in Figure 4. This expanded View of Figure 3 is based on the parameter selection covered in the previous section. In addition, the speed of the aircraft is taken to be 250 m/s, with the angle between observations being 60°. With the beam in the forward-pointing position, a 1 μs pulse is transmitted in this position and the return from the pulse is sampled in time increments determined by the range resolution desired. The sampling occurs along the beam from a 0.5 km minimum range to a maximum range of ~11.5 km. This allows coverage normal to the flight path out to ~10 km. The range resolution is determined by the pulse width and is given by $AR = \tau/2c$, where AR is the range resolution, τ is pulse width, and c is the speed of light. For the 1 μs pulse, approximately 73 samples will be taken in 76 μs. At a pulse repetition rate of 200, the next pulse transmission occurs in 5 ms, when the aircraft has moved 1.25 m. In 0.6 s the aircraft has moved 150 m and 120 pulses have been transmitted. Following the reception of the 120th pulse return, the beam is directed to the rearward angle. If it is assumed that the 60° change (including settling time) requires ~0.2 s, the aircraft has traveled 50 m since the last received pulse in the forward direction. At this point, data would

be collected from another 120 pulse returns. During the period of time required to complete a grid intersection point, altitude variations will occur in the different samples, particularly at the far ranges. To maintain a vertical resolution on the order of the range resolution, the roll axis of the aircraft must be stabilized and the overall altitude variations by the aircraft must be taken into consideration. In the final calculation for the grid point, data from the 120 forward looking pulses will be averaged to obtain a single component value. Likewise, the 120 rearward-looking pulses will be averaged to obtain the second component, and the vector will be calculated for the grid point. In this manner, calculations will be performed for each grid point and a map constructed of the flow field. For this particular configuration a 10 km by 10 km map could be constructed in <2 min. The time between component measurements at the nearest point to the aircraft would be ~ 3 s as compared to the time for the farthest point of ~ 50 s. These times should allow for a relatively accurate measurement of the mean flows surrounding a severe storm.

4. Test Program Plan

NASA expects to select a suitable aircraft for the integration of the pulsed Doppler lidar system by the end of 1978. We hope this will be accomplished as a cooperative endeavor with another group interested in flying correlative sensors. The test program is planned for mid-1980 and will initially involve checkout of the instrumentation system. Once the checkout has been completed, a selected set of data acquisition experiments will be performed in conjunction with other sensors to provide a series of data sets organized in such a manner as to permit the maximum acquisition of correlative data. This will be accomplished by participating in local or regional mesoscale experiments such as the Atmospheric Variability Experiment (AVE) (Hill and Turner, 1977), the Severe Environmental Storms and Mesoscale Experiment (SESAME) (Lilly, 1976), and the Convective Storm Studies (NCAR, 1977). An important objective for the test program is to acquire selected data sets in the vicinity of convective storm development for use in assessing the potential for measurements from satellite remote sensors such as those to be acquired by the VAS sensors from a geosynchronous orbit. Data sets acquired by the test activity will be made available to all interested researchers.

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APPENDIX B

THE MSFC DOPPLER LIDAR SYSTEM

James W. Bilbro and Michael Krause

The Marshall Space Flight Center has been involved in the research and development of coherent Doppler lidars for atmospheric measurement since the first successful measurement of clear air returns in 1968. This effort has led to the development and application of both pulsed and cw systems. In the area of cw measurements, a variety of phenomena have been examined including aircraft wake vortices, dust devils, vertical wind profiles, and smoke plumes. Both airborne and ground based measurements of clear air have been performed with a pulsed Doppler lidar developed by the Raytheon Co. for the Marshall Space Flight Center in 1971. This system has successfully measured gust front wind shear, and clear air turbulence. A modification of the airborne pulsed system is presently underway to allow for the measurement of wind fields in the nonprecipitious regions surrounding severe storms. This modification is being sponsored by NASA's Office of Space and Terrestrial Applications under their severe storms research program.

A block diagram of the Lidar is shown in Figure 1. It is a CO₂, pulsed, coherent Lidar operating at 10.6 μm . Its configuration is shown as a MOPA (master oscillator power amplifier). To obtain an understanding of how the system operates, it is perhaps best to follow through the block diagram. First, the master oscillator is a continuous wave (cw) laser providing approximately 8 watts of linearly polarized radiation at 10.6 μm . A small portion of this output is picked off for use in frequency stabilization of the master laser and for use in an offset locking loop used to maintain the offset local oscillator laser at a 10 MHz frequency offset from the master laser. The main portion of the master laser output is directed to an electro-optic CdTe modulator, where it is chopped into a pulse train of variable width and rate. The width selected for severe storms measurement is 2 μs . The pulse rate is 140 pulses per second. The resultant pulse train passes through an indium antimonide isolator which prevents reflections from the secondary mirror of the telescope from entering the master laser cavity. The pulse train, after being expanded to a diameter of 15 mm, is then directed into a 6-tube, power-amplifier array which provides approximately 40 db of gain. The pulse train next passes through a Brewster window, a quarter-wave plate (which converts the polarization from linear to circular) and into a collimated 30 cm diameter, all metal, off axis telescope where the pulse train is expanded to approximately 24 cm ($1/e^2$) and directed into the atmosphere. These pulses are scattered by particulates on the order of from 1 to 10 μm in size which are naturally entrained in the atmosphere. Some of the scattered light returns along the same optical path as the incident beam, after having been Doppler shifted in frequency by an

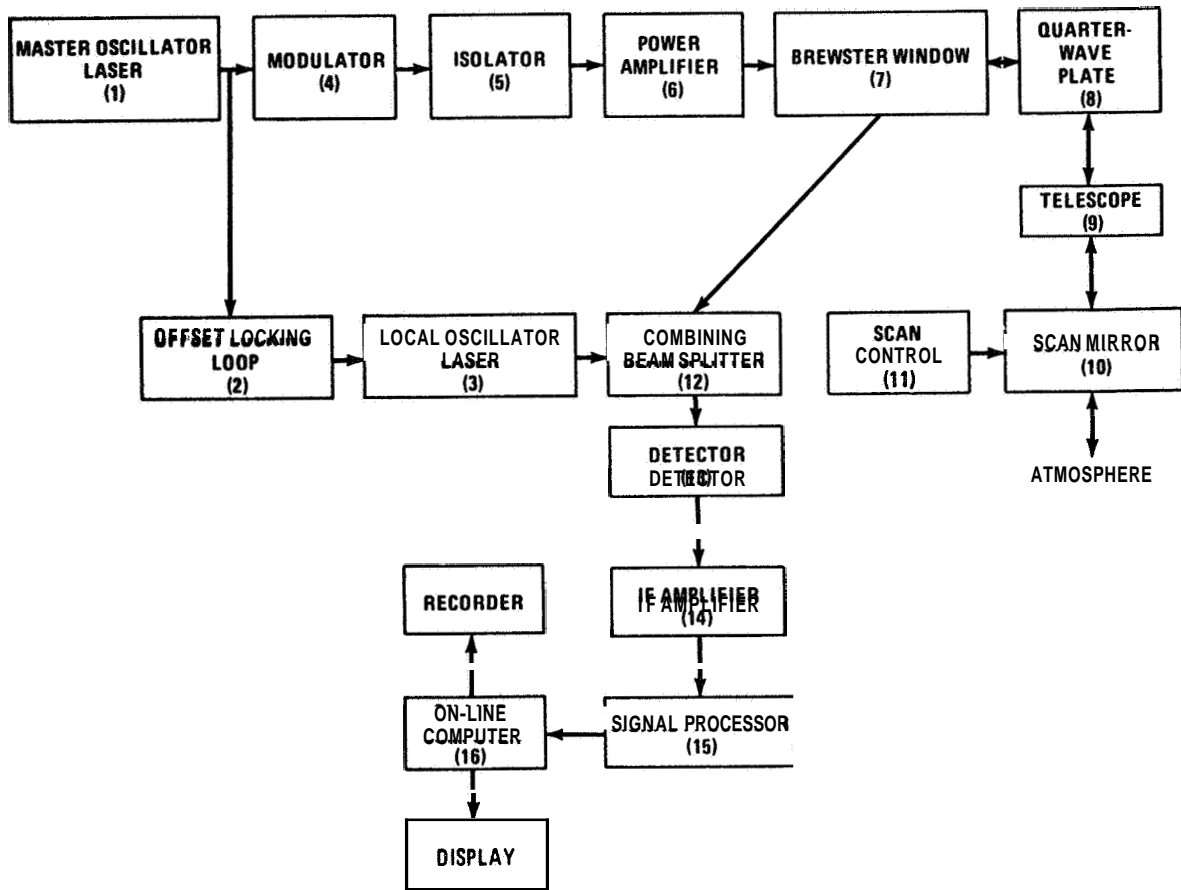


Figure B-1. Simplified Doppler lidar system block diagram.

amount proportional to the radial component of the aerosol velocity, and reversed in its direction of circular polarization. Measurement of this Doppler Shift in frequency is the primary purpose of the Lidar. The backscattered beam is collected by the telescope, passed through the quarterwave plate, and reflected by the Brewster window to the HgCdTe detector, where it is mixed with the LO beam. The reflection from the Brewster plate is enhanced by the change in polarization at the target, which results in linear polarization of the scattered beam at 90° to the polarization of the transmitter. The output of the detector is an fm modulated signal where the modulation frequency is the difference between the LO beam and the backscattered beam. This signal is processed to extract the Doppler mean, width and intensity using a poly-pulse-pair estimation technique. This information is then transmitted to a central timing and control system where it is formatted for transfer to the main computer.

A scanner consisting of two counter rotating Germanium wedges is used to direct the output beam $\pm 20^\circ$ about a line perpendicular to the

flight path of the aircraft. The scanner automatically compensates for the roll and pitch of the aircraft producing a grid of intersection points as shown in Figure 2. At each grid point the horizontal vector velocity component is calculated by the on line computer.

The Lidar system is scheduled to be installed of the NASA/Ames CV 990 in June 1981. Flight tests will be conducted during the latter part of June and the entire month of July.

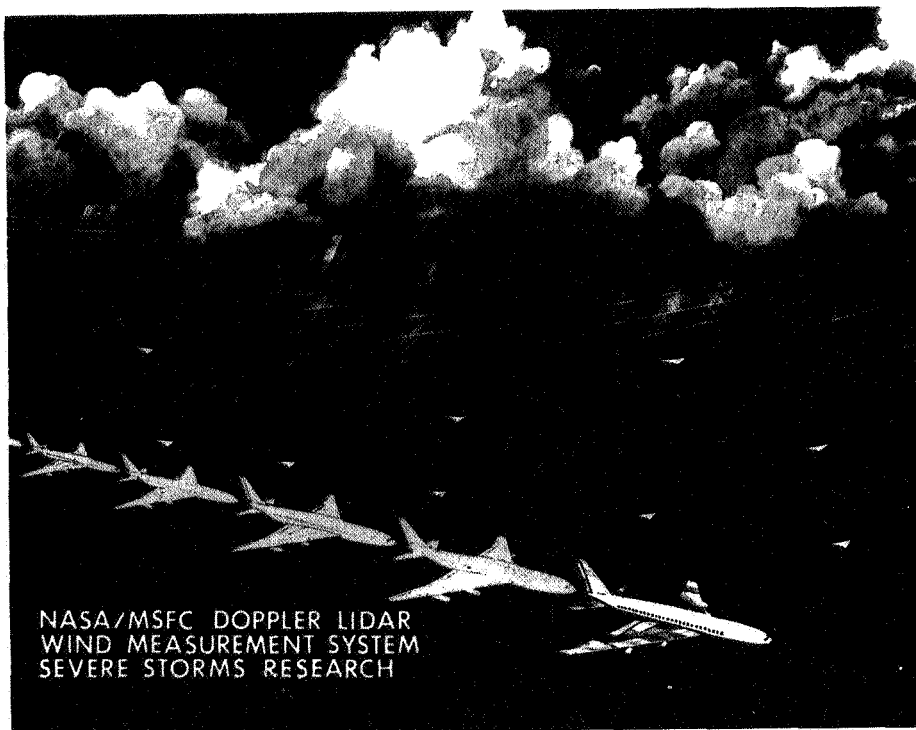


Figure B-2. Severe storm measurement concept.

APPENDIX C

POSSIBLE APPLICATIONS OF MSFC DOPPLER LIDAR SYSTEM

George H. Fichtl and John W. Kaufman

The objectives of this presentation were (1) to provide an interpretation of the Doppler Lidar return, (2) to provide some thoughts on possible application of Doppler Lidar to severe storm research, (3) to present project schedule and, (4) brief participants on plans for the afternoon session.

1. Interpretation of Doppler Lidar Signal - Consider a Doppler Lidar pulse of length L at range R . The Lidar radiation will be backscattered by aerosols at Range R to the Lidar backscatter detector. Each aerosol in the pulse volume at range R will contribute to the backscatter signal at the detector. Furthermore, the backscattered radiation by each aerosol will be Doppler shifted depending on the direction of the line-of-sight component of velocity of the aerosol particle. The net intensity of the backscattered radiation from the scattering volume at range R as a function of Doppler shift at the detector is called a Doppler spectrum. By the very nature of the backscattering process and the fact that there is negligibly small relative motion between the aerosols and the **air**. The Doppler spectrum can be interpreted (in an approximate sense) as being the probability density function of the line-of-sight component of velocity of the **air** within the scattering volume at range R . Thus, the first moment of the Doppler spectrum corresponds to the mean line-of-sight component over the length L and the second moment corresponds to the variance of the line-of-sight component velocity of the **air** parcels within the scattering volume. The diameter of the pulse is three orders magnitude smaller than the length L , so that the lateral extent of the scattering volume results in negligible averaging in the context of the Doppler spectrum. It should be kept in mind that gradients of mean flow along the line-of-sight and the Doppler instrument can produce Doppler spectrum broadening so that care should be exercised relative to interpretation of the Doppler spectrum second moment. However, if gradients of line-of-sight mean flow do not exist along the line-of-sight then the second moment corresponds to the variance of line-of-sight velocity associated with Fourier components with wavelengths less than L with a contribution due to instrument broadening. If the flow is turbulent and an inertial subrange exists for turbulence wavelengths $\lambda \leq \lambda_0$, such that $L \lesssim \lambda$, where λ_0 is the maximum wavelength of the Fourier components in the inertial subrange, then the second moment can be interpreted as being a measure of turbulence kinetic energy dissipation rate to the two-thirds power, i.e., $E^{2/3}$.

2. Possible Applications of the Doppler Lidar System - The severe storm is a complex highly three dimensional flow structure with length scales of motion extending over eight orders of magnitude (100 km to 1 mm) . The Doppler Lidar System can provide measurements associated with the first three orders of magnitude (100 km to 300 m) with respect to the first moment of the Doppler spectrum, and in some cases the next two orders of magnitude (300 m to 1 m) with respect to the second moment of the Doppler spectrum. In light of the previous comments, it appears that fundamental measurements could be made of the detailed structure of the following flow features:

- a. Cold **air** outflow
- b. Warm air inflow
- c. Convergence/divergence and vertical vorticity patterns in cloud free **air** beneath and around the cloud.

The MSFC Doppler Lidar System will provide measurements of horizontal line-of-sight wind velocity at approximately 300 m intervals out to about 10 km. Thus, by applying the scanning feature of the system (see Appendix A) it is possible to construct plane view maps of the above features in the context of the first moment of Doppler spectrum with Nyquist wavelength approximately equal to 600 m over horizontal area extent as large as 10^4 km^2 . The Doppler spectrum second moment data might be used to make inferences about turbulence structure of the cold **air** outflow and warm air inflow.

The experimental state of knowledge of cold air outflow has been summarized in the papers by [Charba (1974), Goff (1976)] . Significant theoretical contributions have been made by Mitchell and Anthes (1976) relative to detailed vertical structure and by Klemp and Wilhelmson (1978) relative to plan view structure. The detailed wind velocity and dissipation rate data that will be acquired with the MSFC Doppler Lidar System will provide one-order of magnitude improved horizontal resolution over the excellent experimentally derived models of Charba and Goff, for altitudes above meteorological tower height. Furthermore, the Doppler Lidar data will provide data sets for application in cold air outflow model verification and may provide insights which could lead to improved analytical/numerical models of the cold air outflow process especially as relates to the complex interaction between the cold **air** outflow and warm air inflow overriding the outflow. Furthermore the Doppler Lidar data sets may provide an opportunity to study the lobe and cleft structure at the leading edge of the cold air outflow in the context of the laboratory work of Simpson (1969, 1972).

Data acquired from Doppler radar (Brandes, 1977) and theoretical/numerical studies (Klemp and Wilhelmson, 1978) have revealed that the severe storm has a complex three dimensional vorticity structure wherein vortex tube stretching, vortex tube tilting and velocity convergence/divergence play key roles. Because the vortex tubes thread through

the cloud and cloud-free air, it may be possible to gain new insights into the vorticity structure of severe storms with the Doppler Lidar used in conjunction with the Doppler radar.

3. Project Schedule - Figure C-1 provides a summary of the project schedule relative to scientific preparation for the FY 1981 summer field test of the MSFC Doppler Lidar System. The flight test plan will be developed based on test options for verifying the Doppler Lidar system and for acquiring data for scientific applications. The test options will be developed by a science working group to be organized in the summer 1980 timeframe.

4. Plans for Afternoon Session - The items suggested for discussion in the afternoon consisted of the following items:

- o What are the major scientific issues associated with severe storms? (Especially those issues wherein the Lidar Doppler velocimeter can play a useful role in acquiring the necessary data for improving our understanding and resolution of these issues.)
- o What data acquisition strategies should be used to acquire data?
 - o Utilization of Lidar Doppler System.
 - o Additional data sources/sets.
- o Determine scientific interests, relative to severe storm research and participation in field program (planning, operation, post-flight data analysis).

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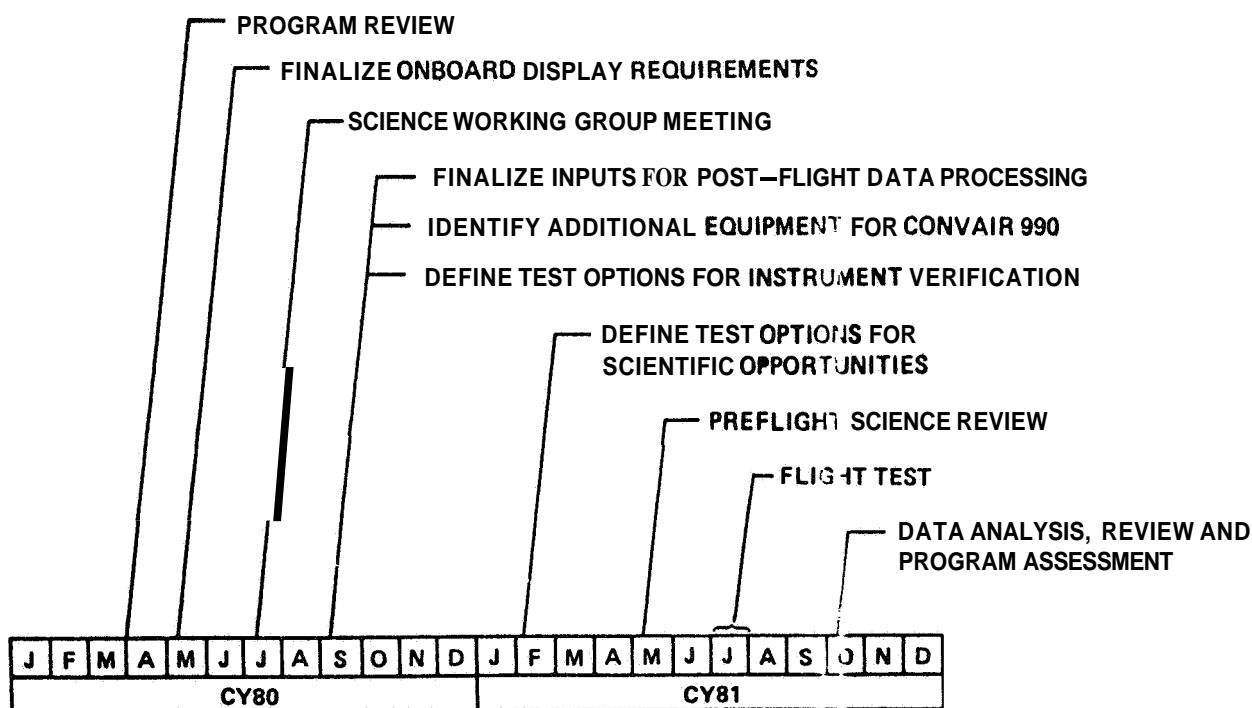


Figure C-1. Summary of the project schedule related to scientific preparation for the FY 1981 field test of the MSFC Doppler Lidar system.

APPENDIX D

COMPARISON OF DOPPLER LIDAR SYSTEM WIND MEASUREMENTS WITH RAWINSONDE MEASUREMENTS

Gregory S. Wilson
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A unique experiment is underway at MSFC to compare vertical vector wind profiles as measured by collocated rawinsonde and Doppler lidar equipment. Numerous rawinsonde releases have been made during the spring of 1980 under various wind conditions. Aloft Doppler lidar measurements were also made during these balloon releases by scanning the lidar antenna in a 360° azimuthal pattern at various elevation angles. This measurement technique provides radial velocity wind speed estimates for a scan volume of conical shape pointing upwards from the lidar antenna. Assuming that the true atmospheric motion is totally horizontal, the vector wind can be determined, as a function of height in the atmosphere, by examining the radial velocities measured in a given horizontal plane cutting through the conical scan volume.

Preliminary comparisons between rawinsonde and Doppler lidar-determined winds are very encouraging. The tentative conclusion is that lidar measurements are within the RMS measurement errors of the rawinsonde systems. A typical example of the types of comparisons that have been produced to date is shown in Figure D-1. By continuing these types of measurements, a statistical data base of comparative wind measurements will be obtained that can provide a benchmark error analysis of lidar winds to be used in future atmospheric measurement programs of all types, particularly in the field of mesometeorology.

*Universities Space Research Association Visiting Scientist.

FLIGHT 1
 MSFC RAWINSONDE PROFILE DATA
 1601Z 28 FEB., 1980

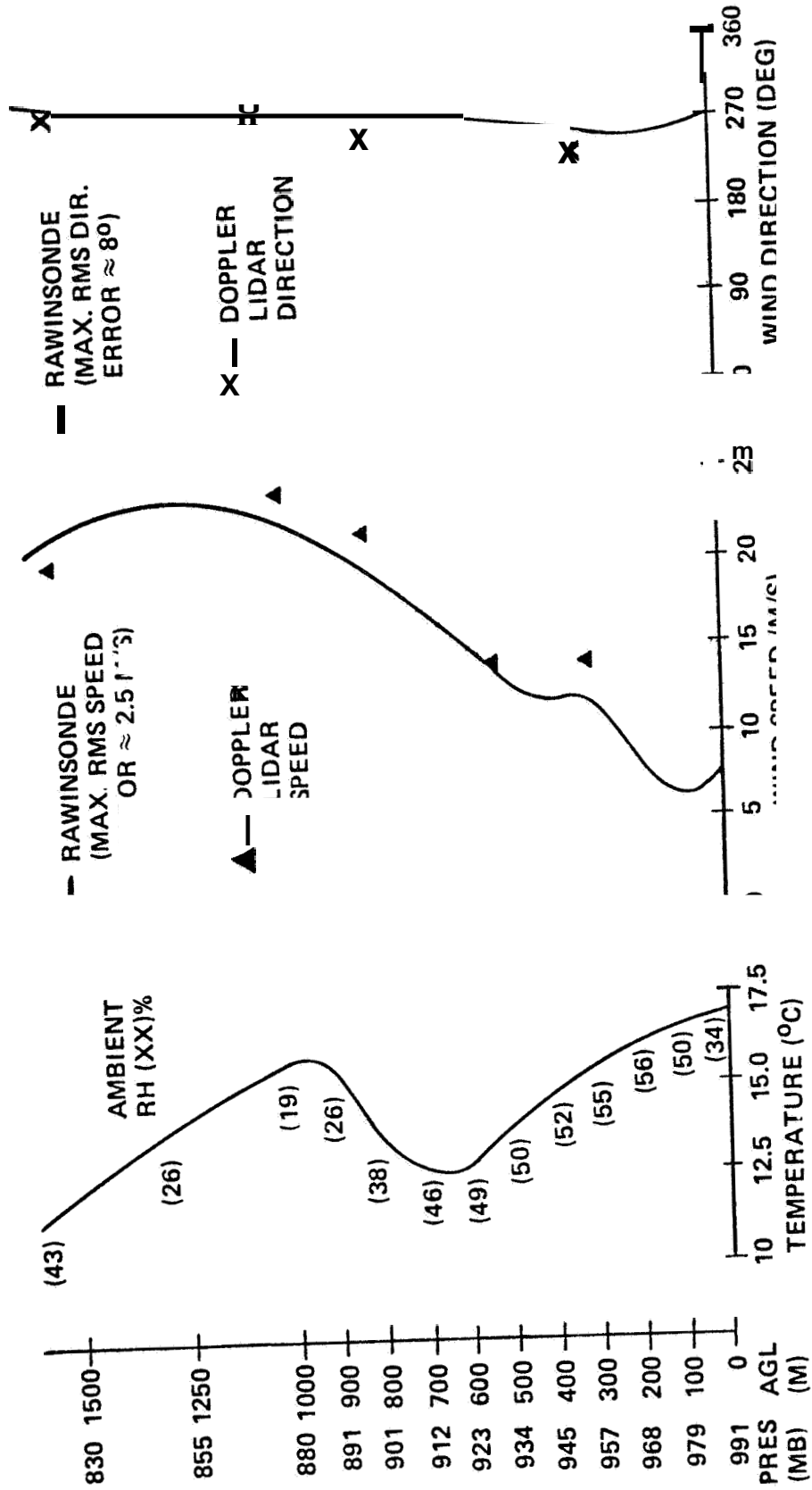


Figure D 1. Rawinsonde versus Doppler Lidar vertical wind profile comparisons

APPENDIX E

AGENDA

MEETING ON MSFC'S AIRBORNE DOPPLER LIDAR WIND
MEASUREMENT SYSTEM

When: April 1, 1980, 9:00 a.m. - 4:00 p.m.

Where: NASA-Marshall Space Flight Center, Space Sciences Laboratory
Conference Room, West End Building 4481

- 9:00 a.m. Introductions and Project Overview .. W. W. Vaughan/MSFC
J. Dodge/NASA HQS*
- 9:30 a.m. Doppler Lidar System. J. Bilbro/MSFC
a. Past Experience
b. System Concept and Development Status
c. Tentative Flight Experiment Schedule
d. System Discussion
- 11:30 a.m. Potential Scientific Research Topics **
(Overview).. G. H. Fichtl/MSFC
J. W. Kaufman
- 12:00 Noon Lunch ***
- 1:00 p.m. Detail Discussion Period G. H. Fichtl
J. W. Kaufman
- 4:00 p.m. Brief Summary and Adjourn W. W. Vaughan
J. Dodge, etc.

* Dr. James Dodge, NASA HQS was unable to attend.

** This presentation was continued at 1.00 p.m. at which time Dr. Greg Wilson also presented wind velocity profiles simultaneously measured by the rawinsonde and Lidar Systems at MSFC.

*** A brief tour was made to the MSFC Doppler Lidar site just after lunch.

APPENDIX F

ATTENDANCE LIST TO THE MEETING ON MSFC'S AIRBORNE DOPPLER LIDAR WIND MEASUREMENT SYSTEM HELD AT NASA/MSFC ON APRIL 1, 1980

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INVITEES WHO WERE UNABLE TO ATTEND

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APPROVAL

EXPLORATORY MEETING ON AIRBORNE DOPPLER LIDAR WIND VELOCITY MEASUREMENTS

Edited by George H. Fichtl, John W. Kaufman, and William W. Vaughan

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.



CHARLES A. LUNDQUIST
Director, Space Sciences Laboratory