# DLSM: A Coherent and Direct Detection Lidar Simulation Model for Simulating Space-based and Aircraft-Based Lidar Winds

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## ABSTRACT

The U.S. Air Force seeks reliable wind measurements in the vicinity of clouds from the perspective of a satellite platform or high altitude aircraft. These wind observations may be used as input to tactical decision aids or assimilated into weather forecast models. There is also interest in making direct wind measurements below clouds by sampling through optically thin gaps. Ground-based and airborne-based lidars have demonstrated the ability to make direct measurements of horizontal winds based on determination of the wind-induced Doppler shift in the backscatter signal. To develop an optimal design concept for space-based lidar platforms, a simulation model has been developed to address questions of optimum laser wavelength, pulse length, minimum power, scanning strategies, optimal signal processing and wind computation algorithms. This paper presents an operational simulation model, the Defense Lidar Simulation Model (DLSM), for space-based/airborne coherent and incoherent Doppler lidar wind sounders that produces simulated Doppler lidar winds using either global or mesoscale atmospheric model wind fields.

**Keywords:** Doppler Wind Lidar, Lidar Simulation Model, Winds, OSSEs

## 1. THE DEFENSE LIDAR SIMULATION MODEL (DLSM)

Under a 1996 SBIR Phase II contract, Simpson Weather Associates (SWA) developed a prototype coherent Doppler wind lidar simulation model[1] for the DOD to use in evaluating future space-based Doppler lidar concepts and for simulating airborne lidar observations. The DLSM was based upon existing Doppler wind lidar simulation models[2, 3, 4] that produce simulated Doppler lidar winds and corresponding errors using global atmospheric model wind fields. Under the SBIR, SWA added a GUI, expanded lidar scanning options, an airborne platform simulator, fine mesh mesoscale atmospheres and improved representation of cloud optical properties and cloud porosity. Over the past few years, the DLSM has continued to evolve with enhancements of improved characterization of signal processing algorithms, high resolution global atmospheric fields and an incoherent Doppler lidar wind sounder algorithm. Currently, the DLSM is being used in the Observing System Simulation Experiments (OSSEs) [5, 6] to evaluate several spaced-based Doppler Wind Lidar (DWL) technologies and in the Convection And Moisture Experiment (CAMEX) [7, 8] to assess the potential impact of airborne DWL data in hurricane track forecast models.

## 2. MODEL OPERATION

The DLSM simulates a space-based or an airborne Doppler lidar wind sounder providing global or regional three-dimensional simulated lidar winds and corresponding errors. The major modules of the DLSM involve the satellite/aircraft, scanner, laser, signal processing, atmospheric library, line of sight wind, horizontal wind component and error models as shown in Fig. 1. The DLSM is a unique set of computer models that addresses various types of questions of the feasibility and optimal functionality of a space-based or airborne Doppler lidar systems. In addition, the DLSM is also designed to address engineering trades, measurement accuracies (line of sight and horizontal wind vector), measurement representativeness, resolution and coverage.

Execution of the DLSM invokes the DLSM Welcome Screen: the model's main control screen. The DLSM Welcome screen has five options: Configure Model Inputs, Run the Lidar Simulation Model, Toolbox (stand alone model and graphics), Model Input Limits Editor and exit DLSM. The DLSM operation is controlled by three model configuration files: Operation, Platform/Lidar and Atmospheric. All three files are mandatory for the Lidar Simulation Model to run. The three model configuration files are either created manually or read in from existing files. The user is allowed to edit

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new or inventory loaded files. Once the user has defined the Operation and Platform/Lidar configuration files, the user must create a laser shot coverage file by running the Platform/Laser Shot model or use an existing shot coverage file.

In the Configure Inputs window, the user enters DLSM inputs, reviews his inventory of DLSM input files, loads existing files, and edits existing files. From Configure Inputs screen, the user can run the Platform/Laser Shot model and the Atmospheric Generator Model (AGM). The Platform/Laser Shot Coverage (SCV) is a stand alone model that allows the user to simulate satellite and aircraft missions with a variety of laser scanner options such as supports conical, fixed-beam and step-stare beam scanners. It allows the user to address platform track, laser coverage and shot management issues and trades. For aircraft missions, the SCV reads in an existing aircraft data file containing aircraft altitude, location, heading, and attitude information as a function of time along a flight path. The aircraft data files can be real missions or simulated ones. The Atmospheric Generator Model (AGM) is made up of an extensive set of integrated atmospheric models and data bases. The AGM provides meteorological options from control fields, correlated generated fields, mesoscale fields (29 km Eta) to global meteorological fields (ECMWF T213 and T106). The AGM provides opaque clouds, cirrus clouds, aerosol backscatter, molecular attenuation, atmospheric turbulence and terrain information.

From the DLSM Welcome Screen, Run LSM executes the Lidar Simulation Model to produce simulated DWL wind information. There are icon buttons to allow the user to pause the simulation run in order to refine selected model inputs or to graph model inputs and intermediate outputs as the model runs.

From the DLSM Toolbox screen, the user can graph platform coverage, laser shot coverage, global and mesoscale atmospheric variables, laser line of sight products and laser horizontal wind products. The Model Inputs Limits Editor (MILE) allows the user to customize his input limits that the DLSM input algorithms use to screen all user's inputs. All screens have a help option.

The DLSM was designed on a HP APOLLO 9000 workstation. All DLSM inputs and graphic routines are coded in HP C, Xlib and XRT/3d. The Doppler lidar simulation models are coded in HP FORTRAN/9000. A PC version of the DLSM has been developed using Visual Fortran 90, Visual Basic and Surfer. Recently, the lidar simulation models with an ascii I/O algorithm was ported to a CRAY C90 for the OSSEs

## 3. CURRENT MODEL APPLICATIONS: OSSEs AND CAMEX

### 3.1 OSSEs

Space-based application of Doppler Wind Lidar technology is without heritage, thus, optimal design of DWL systems for space deployment must rely upon computer model studies. These model studies include efforts with DWL performance models, atmospheric circulation models and atmospheric optical models [9, 10, 1, 3, 2].

The steps between a notional concept for a DWL and the blueprints for instrument construction include a considerable amount of performance modeling and, for space-based systems, an intensive series of OSSEs. During and subsequent to the Laser Atmospheric Wind Sounder (LAWS) study [11], a method for assessing the potential impact of a new DWL observing system was established. Instrument parameters are provided by the engineering community along with scanning or sampling strategies from the science community. A "Nature Run" is provided by a weather prediction center (e.g., ECMWF) with the realism of the "Nature Run" assessed by a second group of analysts. A series of pre-OSSE instrument performance simulations are conducted using the "Nature Run" as input. Finally, a candidate(s) DWL concept is chosen for a full OSSE, and an impact study is then conducted and evaluated by a technology neutral group.

SWA is currently tasked to provide instrument performance simulations for both direct and coherent detection DWLs and to provide simulated data sets for the following OSSEs:

- OSSEs for adaptive targeting of less than 100 % duty-cycle DWL concepts
- OSSEs for DWLs with PBL/cloud sensitivity
- OSSEs for DWLs with full tropospheric sensitivities
- OSSEs for hybrid technology DWLs using shared platform resources

Due to the potentially large volume of data that can be generated by simulating Space-based DWL a revised plan for conducting bracketing OSSEs has been agreed upon.

The bracketing OSSEs are meant to explore the bounds of the potential impacts of a space-based wind sounder on today's operational forecast models for several "technology neutral" observation coverage and measurement error characterizations. By "technology neutral" we mean that the instrument details are ignored but the general sense of how a lidar measurement is made is retained. Thus, the following aspects of making wind measurements with space-based Doppler wind lidars are captured:

- Observations from a sun synchronous polar orbit
- Cloud obscuration and fractional coverage
- Variance of the wind on scales ranging from the illuminated cylindrical volume (~ 1km x 10 km) to the targeted resolution volume (TRV) of 200 km x 200 km x 1 km.
- Winds derived from sensing the molecular returns from the cloud free atmosphere
- Winds derived from aerosols of any concentration
- Winds derived from aerosols of high backscatter returns such as those from the PBL and clouds
- Distributed vs. cluster sampling of the wind field within the TRV.

There are several reasons for conducting a series of bracketing OSSEs prior to performing future OSSEs for very specific instrument concepts. First, we want to know the "ultimate" sensitivity of the OSSE to the atmospheric parameter in question...in this case, winds. In other words, the question is how much of an impact would be reported if perfect wind observations from the Nature Run were available to the operational model. If the answer was "hardly detectable", then there would be no reason to continue with the rest of the planned OSSEs. The second reason for the bracketing OSSEs is to provide some measure of the relative return on investment for several general DWL data products. In this case, some general form of "cost/benefit" analyses can be achieved. A third reason is to develop the tools to evaluate the more specific concepts that will be proposed to meet some stated requirements. A fourth reason is to develop the understanding and experience of assimilating DWL data products long before the instrument is launched. Such a long lead-time increases the likelihood that the instrument design may also benefit from the OSSE results.

The bracketing OSSEs listed in Table 1 are designed to establish the range of impacts that could be expected from a range of DWL data product coverages and accuracies as they compare with a "reference impact". The "reference impact" is that associated with the use of perfect wind observations from the Nature Run. The perfect observations are constrained to the temporal and spatial coverage of a space-based observing system. Otherwise, no cloud or subgrid scale wind variance effects are simulated. The data product simulated for the "reference" OSSE (R) is a wind profile from a Nature Run grid point closest to the center of a 200 km x 200 km data grid. This "reference" OSSE does not map to any real DWL. However, the data set can be used with several assigned RMSEs to test for basic accuracy sensitivities of the OSSE system.

The next four OSSEs in Table 1 have been defined to explore selected or limited data product coverages that may, in a very general sense, be mapped to DWLs of differing coverage potentials (referred to as the Coverage Series). The "Accuracy Series" of experiments uses the same coverage scenarios as the Coverage Series but varies the instrument measurement accuracy. Cloud and wind variance effects are invoked in all of the OSSEs except for the "reference" OSSE (R).

The Experiment 1 distributed data product , shown in Fig. 2, is meant to represent a very sensitive DWL that is only prevented from making an observation by optically thick clouds. In some parlance, this data product would be referred to as the Holy Grail (200 km x 200 km version). The coverage and accuracy ($\sigma_o$ << 1.0 m/s) imply DWL systems which are well beyond the current state of the art. In the "Accuracy Series" of OSSEs, the cases where $\sigma_m$ <= 1.0 m/s would map to all coherent systems, while increasing values of the measurement error would map to less and less capable direct detection systems.

Experiment 2 distributed data product, shown in Fig. 3, is designed to evaluate the relative impact of wind data that is obtained only from clouds or the planetary boundary layer. The resulting data product might be similar to that obtained from a very modest sized coherent lidar. i.e., very accurate measurements from single shots. As various amounts of measurement error are added to the base data product, the data product begins to map to a direct detection aerosol lidar.

As shown in Fig. 4, the Experiment 3 distributed data product represents a distributed data product that would be obtained with an instrument that would provide useful data only when there was a cloud free scene. Since a totally cloud free scene is a very rare event for a 200 km x 200 km target area, we have used 50% cloud cover as the cutoff for useful data. This product may map to the data product of a system that relies solely on molecular returns.

Finally, the Experiment 4 distributed data product, shown in Fig. 5, represents a bounding extreme in horizontal coverage. Whereas the swaths of data in OSSE Experiments R, 1, 2 and 3 were all ~ 2000 km wide, the data in this case is obtained from a non-scanning instrument. The resulting data pattern is a single LOS profile provided every 200 km along the satellite ground track. The data product coverage in the vertical is consistent with the same rules for Experiment 1, except that the shots within a 200 km x 200 km area are assumed to be clustered within a very small area of a few tens km dimension.

### 3.2 CAMEX

A collaborative effort is ongoing between SWA and Colorado State University (CSU) in which the nested RAMS model is being used to investigate the impact of CAMEX 3 measurements, dropwindsondes and moisture from the Lidar Atmospheric Sensing Experiment (LASE), on hurricane track and intensity forecasts. The 1998 Atlantic Hurricanes Bonnie and Danielle are being used as case studies. The experiments are using the DLSM to explore potential DWL data coverages that would result from an optimally performing airborne or space-based lidar. Several experiments are underway or being planned in which the analyses and forecast fields of the Eta model, the NCEP Reanalysis, and the CSU RAMS during Hurricanes Bonnie and Danielle are being used to provide the "real" atmosphere for the DLSM.

Figure 6 shows the potential for satellite laser wind coverage over a hurricane such as Fran (Sept 1996). The simulation of the satellite orbit is for a proposed NPOESS configuration (i.e., 833-km altitude and 45° nadir scan angle). The figure shows that given ~ 1800 km swath width, twice daily coverage of such storms will provide numerous potential wind estimates.

## 4. CONCLUDING REMARKS

Global measurement of tropospheric wind has been widely recognized as potentially the most significant contribution of satellite remote sensing to existing global meteorological observations. Most of the world's oceans are largely devoid of accurate wind measurements, a deficiency that can best be addressed from space. The deployment of a space-based Doppler Wind Lidar would provide the capability to address many of the key issues such as hydrologic and biogeochemical cycles, planetary scale dynamics, atmospheric-oceanic heat transport. Equally important, it would provide critical wind information for improved operational weather forecasting, and for safe, efficient, and effective military and commercial aviation operations.

## ACKNOWLEDGMENTS

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Table 1. **Doppler Wind Lidar Bracketing OSSEs (Coverage Series)**

| | Reference | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Description of data product without regard to specific DWL technology | Perfect u,v observations from an orbiting instrument at single points within the TRV. No cloud or sub-grid wind variability effects accounted for. | Ultimate DWL that provides full tropospheric soundings, clouds permitting. | An instrument that provides only wind observations from clouds and the PBL | An instrument that provides mid and upper tropospheric winds only down to the levels of significant cloud coverage. | A non-scanning instrument that provides full tropospheric soundings, clouds permitting, along a single line that parallels the ground track |
| Vertical domain (km) | 0-20 | 0-20 | 0-20 | 3-20 | 0-20 |
| Target Volume (z>2km) (kmxkmxkm) (z<2km) | 200 x 200 x 1<br>200 x 200 x .25 | 200 x 200 x 1<br>200 x 200 x.25 | 200 x 200 x .25 | 200 x 200 x 1 | 200 x 200 x 1<br>200 x 200 x.25 |
| Swath width (km) | 2000 | 2000 | 2000 | 2000 | <200 |
| C: clustered shots<br>D: distributed shots | C | C & D | C & D | C & D | C & D |

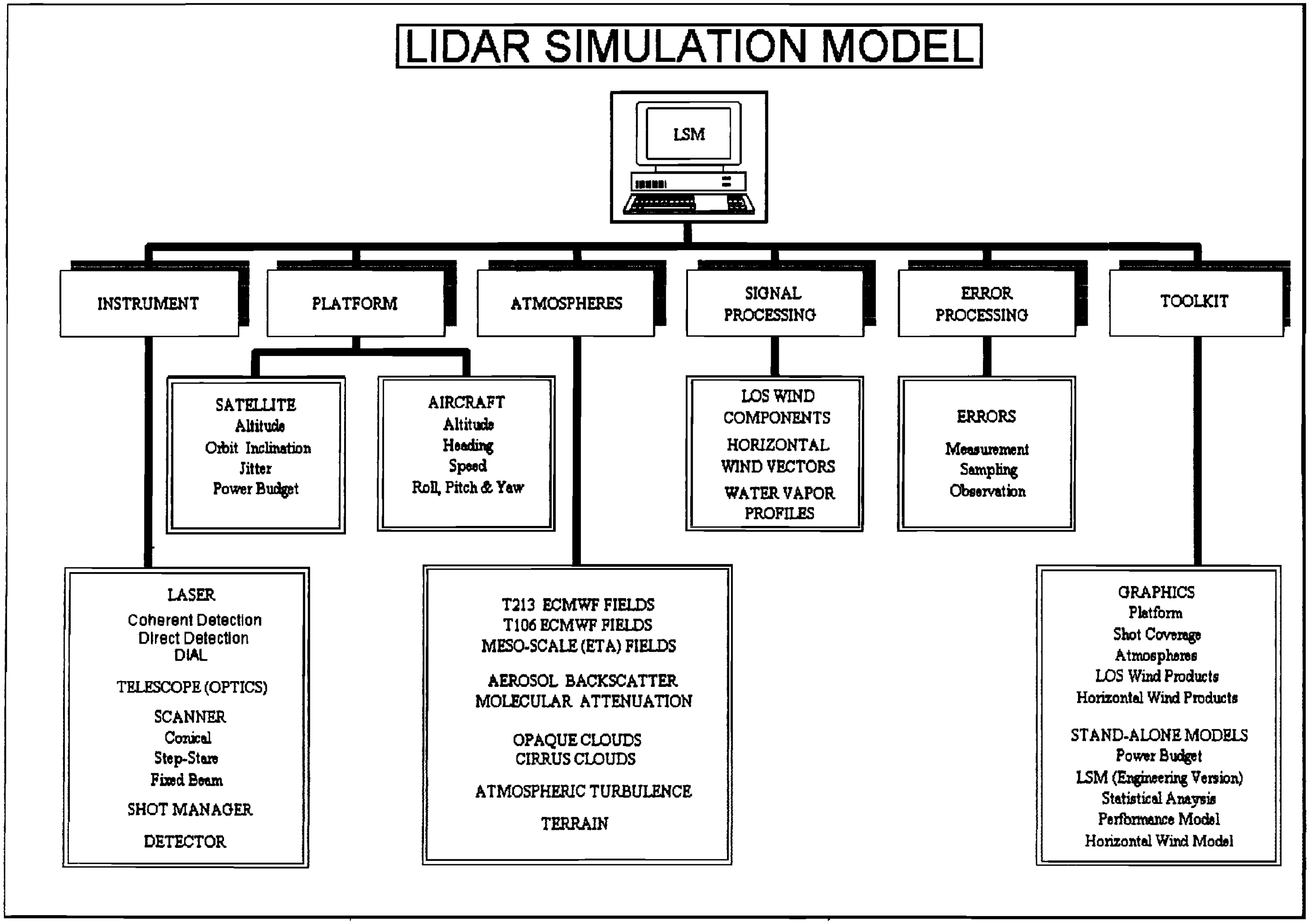
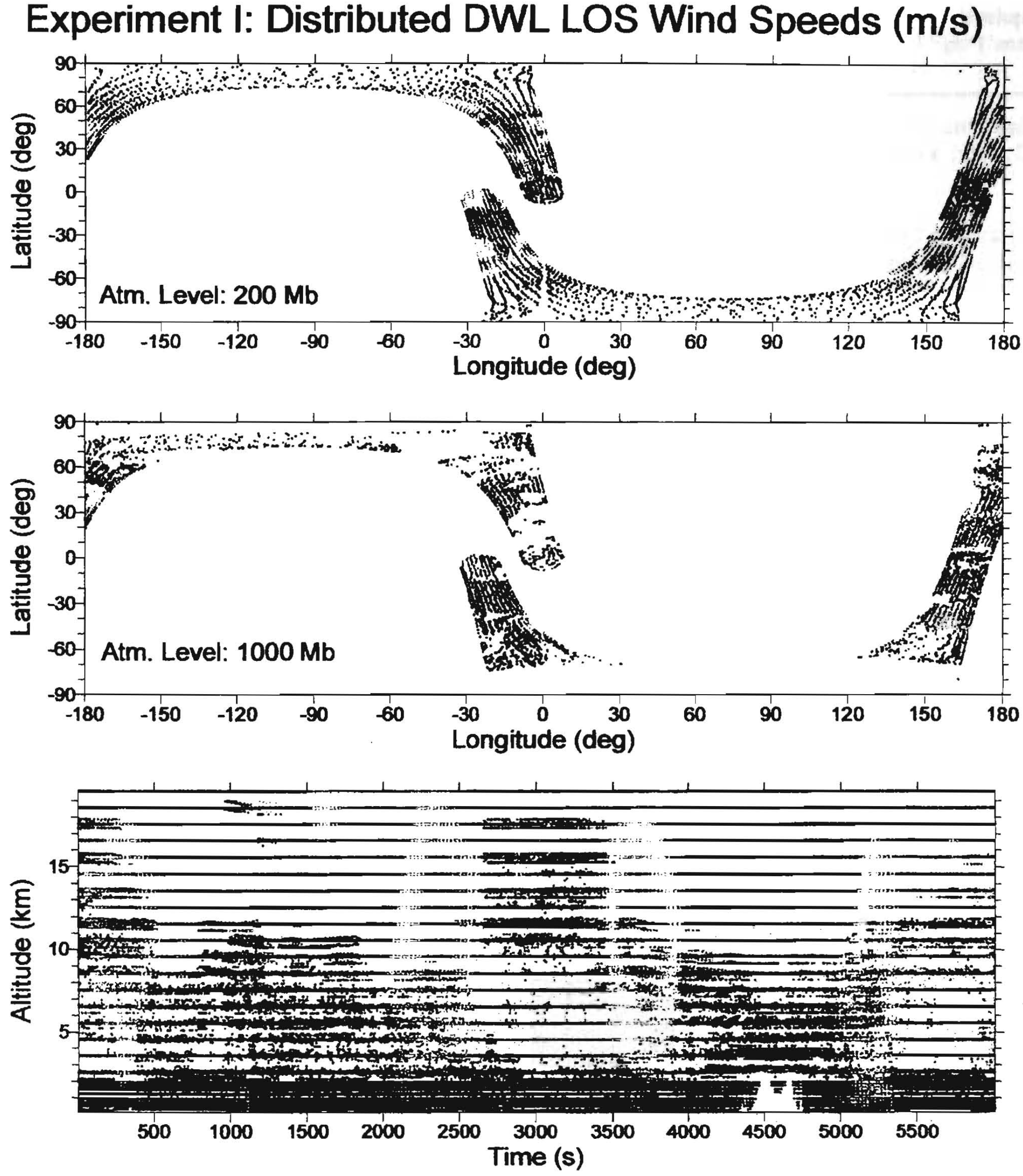


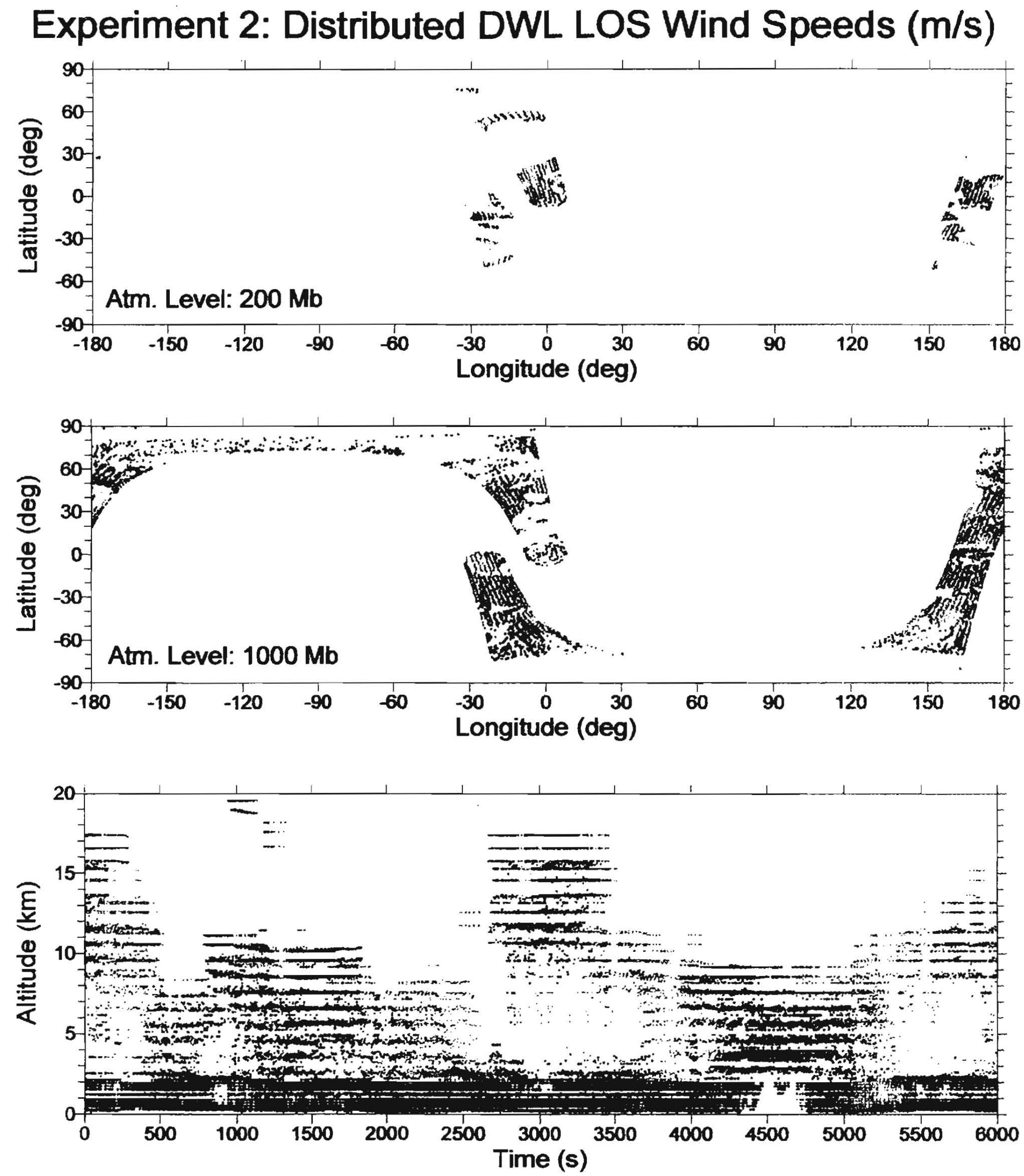
Fig.1. Block diagram of the DLSM.



Experiment I: Distributed DWL LOS Wind Speeds (m/s)

**Simulation: NPOESS/OP on T213 Nature Run 02/06/93 for 00Z to 03Z**
**Satellite Height: 833 km  Nadir Scan Angle: 45 deg  PRF: 12.5 Hz**
**Resolution Volume: 200 km X 200 km X 1 km above 2 km MSL**
**Resolution Volume: 200 km X 200 km X 250 m below 2 km MSL**

Fig. 2. Coverage diagram for an NPOESS/OP space-based Doppler lidar for the bracketing OSSE experiment 1 (distributed).



Simulation: NPOESS/OP on T213 Nature Run 02/06/93 for 00Z to 03Z
Satellite Height: 833 km Nadir Scan Angle: 45 deg PRF: 12.5 Hz
Resolution Volume: 200 km X 200 km X 1 km above 2 km MSL
Resolution Volume: 200 km X 200 km X 250 m below 2 km MSL

Fig. 3. As for Fig. 2 except for Experiment 2.

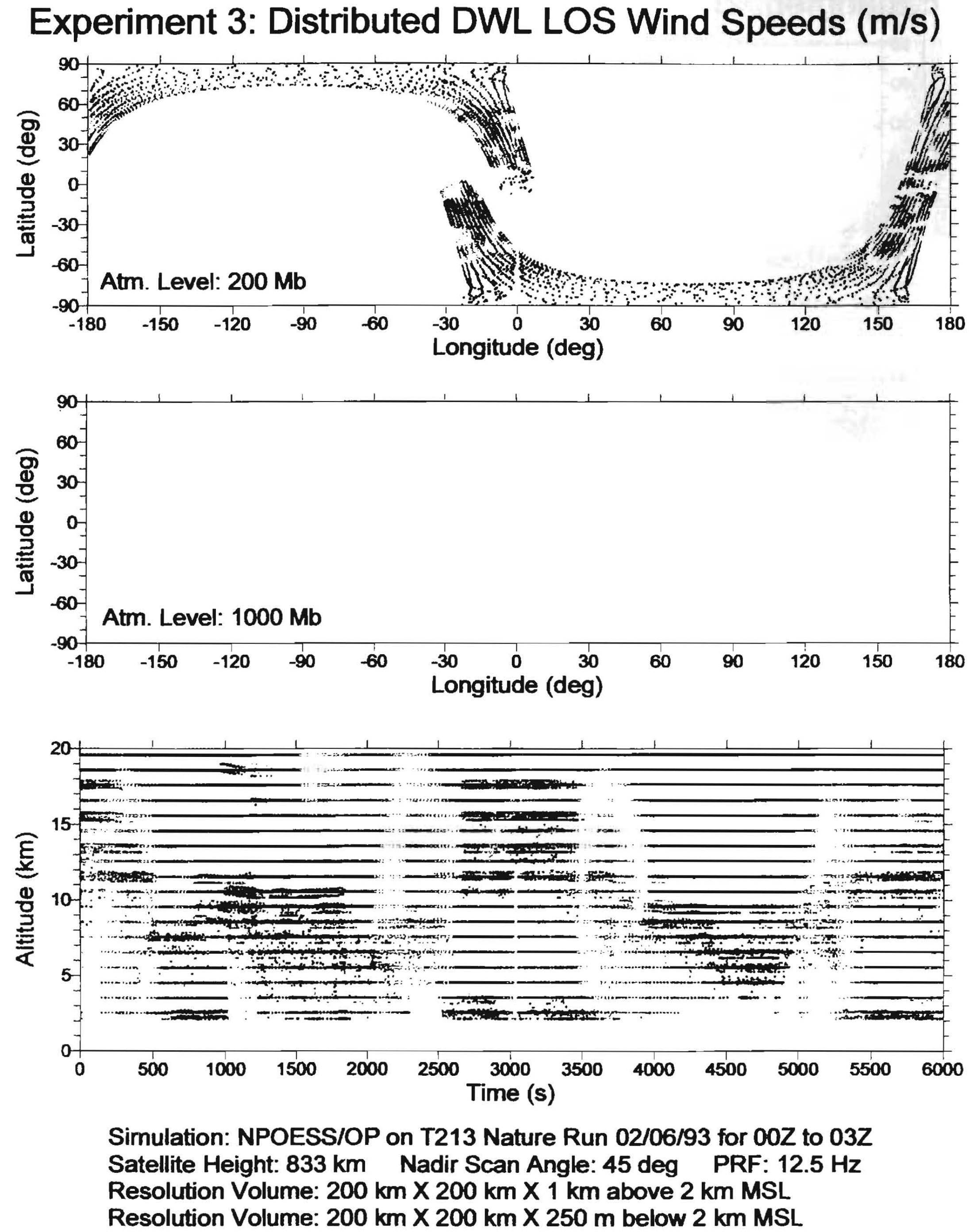


Fig. 4. As for Fig. 2 except for Experiment 3.

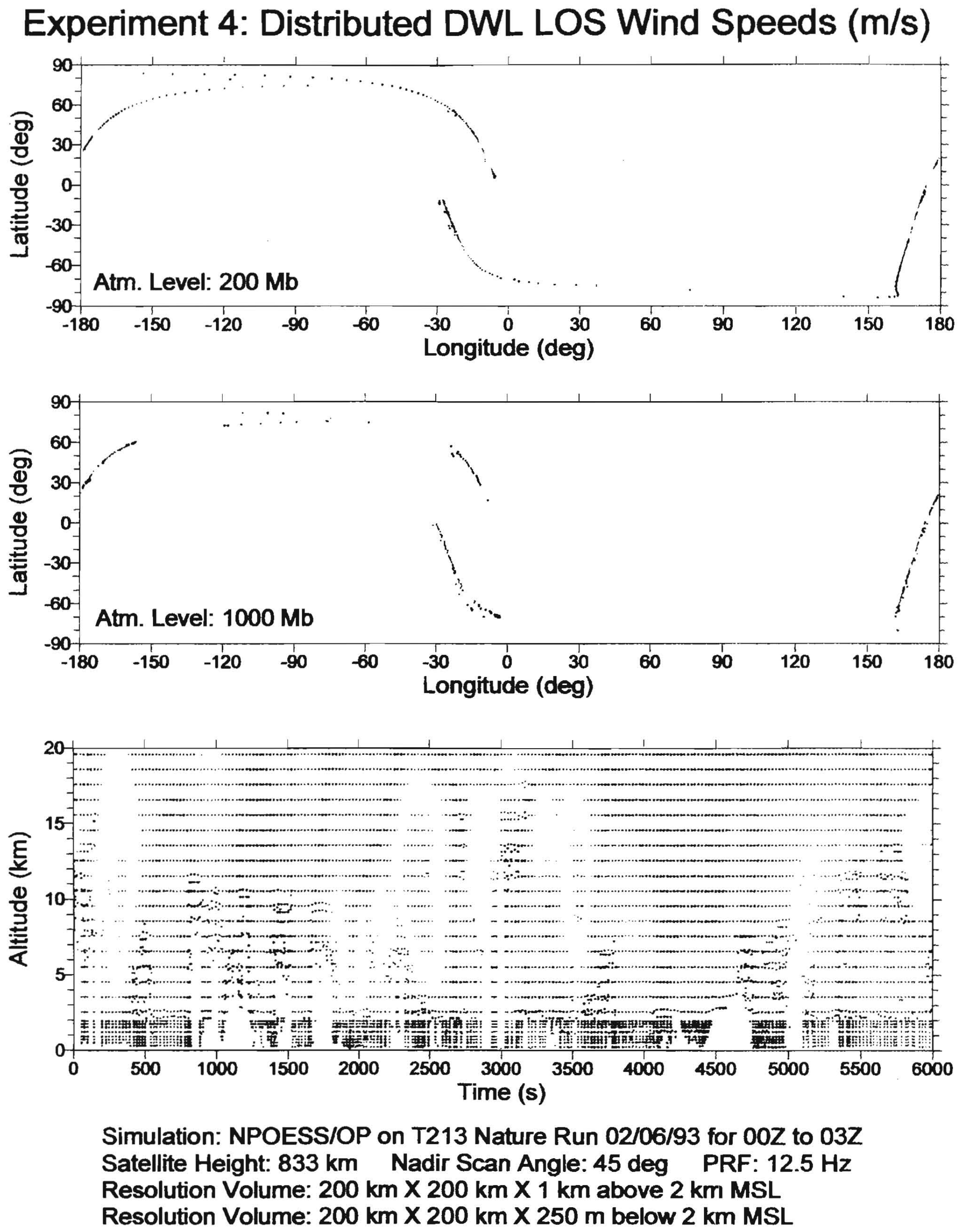


Fig. 5. As for Fig. 2 except for Experiment 4.

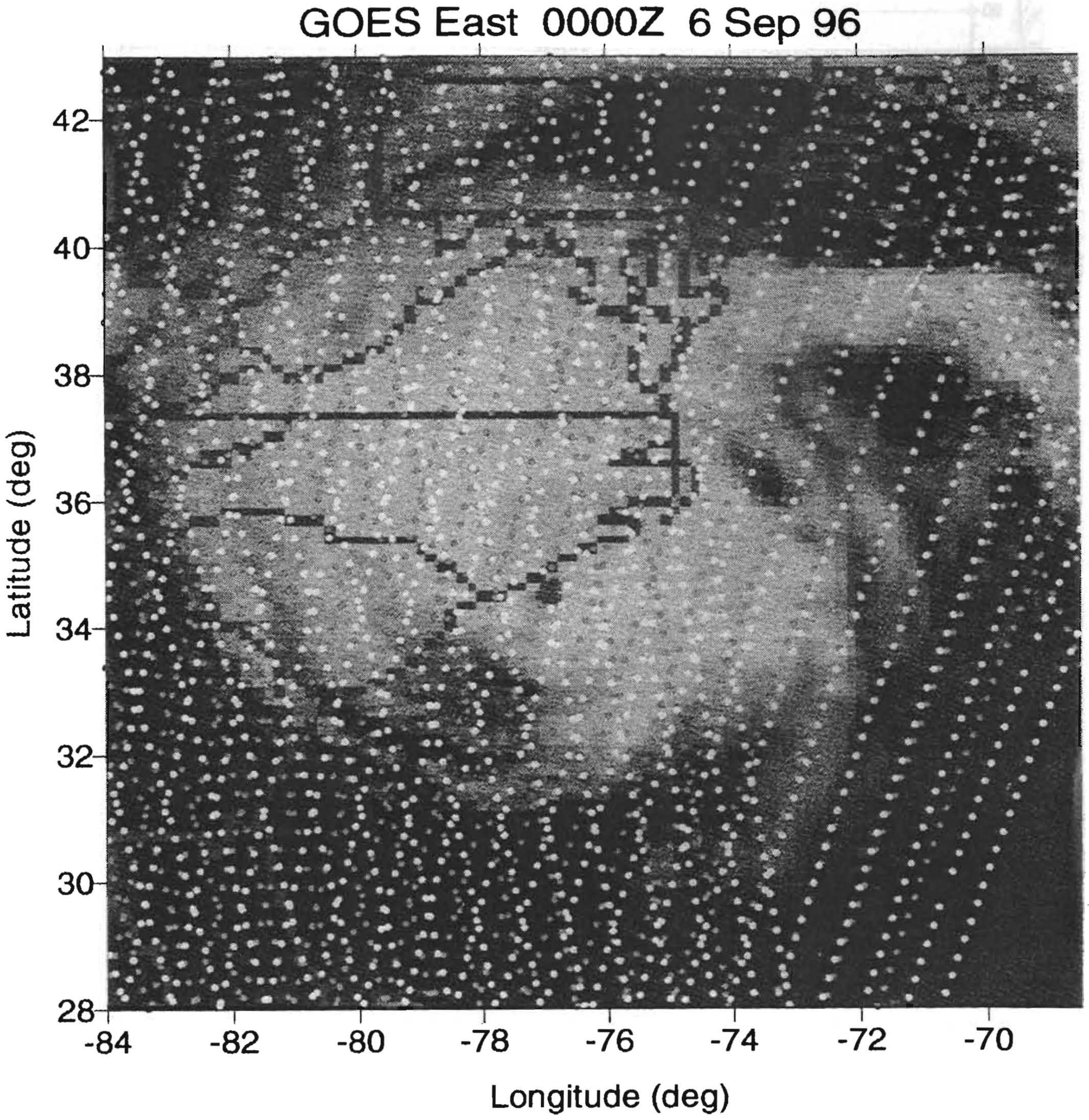


Fig.6. Simulated 24-hr Doppler lidar coverage over Hurricane Fran (9/6/96).

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