THE FLOWS AUTOMATIC WEATHER STATION NETWORK*

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1. INTRODUCTION

Lincoln Laboratory is operating a network of 30 automatic weather stations for the FAA as part of the ongoing FLOWS (FAA-Lincoln Laboratory Operational Weather Studies) Project, which focuses on developing techniques for automated hazardous weather detection in airport terminal areas using NEXRAD-like Doppler weather radars. The stations, designed to measure temperature, relative humidity, barometric pressure, wind speed, wind direction, and precipitation amounts, originally used one of the first commercially available data collection platforms (DCPs) to transmit 5-min averaged data to the GOES satellites. Under FAA sponsorship, Lincoln has procured modern DCPs and has refurbished and modified the sensors to create a reliable 30 station network capable of transmitting one minute averages of the variables mentioned above, as well as the peak wind speed each minute and some internal diagnostic variables, on a single GOES satellite channel. The complete system is described and some performance results from the FLOWS 1984-1985 Memphis operation are presented.

2. HISTORY OF THE WEATHER STATIONS

The automatic weather stations, first used by Lincoln Laboratory in the summer of 1983, were developed by the US Department of the Interior Bureau of Reclamation's Office of Atmospheric Resources Management in the late 1970's (Harrison, *et al.*, 1979). These stations were given the name PROBE, standing for Portable Remote OBservations of the Environment. There was a basic research need at that time for a meteorological data collection network that would allow short term predictions of convective activity, could provide good time resolution, and could be installed and operational in very little time without the need for laying power or telephone data lines.

The stations, shown in Fig. 1, were designed to transmit averaged meteorological variables at regularly timed intervals to the GOES (Geostationary Operational Environmental Satellite). The data are relayed by the satellite back to earth where they are collected by the NOAA National Environmental Satellite, Data, and Information Service's (NESDIS's) ground station on Wallops Island and by anyone with a receiving station tuned to the correct channel (Fig. 2). The primary advantages of collecting the data this way are that the sites almost never have to be visited if they are working properly, the stations can be located in any type of terrain without line-of-sight transmission problems, and, if the transmission schedule permits, the data can be utilized in real-time for nowcasting purposes. The power for the stations is provided by a 12V deep cycle battery which is continuously trickle-charged during daylight hours by the solar panels.

The FAA arranged for the Bureau of Reclamation to furnish 25 of these PROBE stations to Lincoln Laboratory to be operated in the vicinity of Hanscom Field (Bedford, MA) in support of the FLOWS Summer 1983 Doppler radar experiments with FL-1, the Lincoln-built radar system at MIT (Wolfson, *et al.*, 1984). A number of problems caused by the use of DCPs and sensor interfaces that had become old and trouble prone, and by poor sensor calibration procedures prevented successful data collection that summer. However, even if the equipment had worked perfectly, the limitation of 5 minute data averages for studies of low-altitude wind shear, such as microbursts, would not have been acceptable.

During the following months, new highly reliable microprocessor-based Data Collection Platforms were purchased for each station. The sensors were tested, refurbished, and calibrated in order to insure the accuracy of the measurements. Also, the number of stations in the network was increased from 25 to 30 to allow expansion of the spatial coverage without extending the average inter-station spacing.

The Memphis International Airport was chosen as the focus for the initial FLOWS FL-2** Doppler radar tests. The mesonet was operated continuously from May through November, 1984 (7 months) and from February through October, 1985 (9 months). The FLOWS Project then moved to Huntsville in 1986 to participate in COHMEX (Dodge, *et al.*, 1986).

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** FL-2 is the FAA-Lincoln Laboratory transportable Doppler weather radar testbed (Evans and Johnson, 1984).

3. WEATHER STATION INSTRUMENTATION

For each sensor on the automatic weather stations, a brief technical description is presented below. The sensor types and measurement specifications are listed in Table I. More detailed technical information is given by Wolfson, *et al.* (1986).

3.1 Anemometer

The FLOWS wind speed sensor consists of a cup anemometer mounted on a common cross arm with the wind vane. The cross arm height on the station is 6.8 meters above ground level. Wind speed is derived from a photo chopper disk assembly attached to the lower end of the anemometer shaft.

3.1.1 *Anemometer Modifications*

Many of the anemometers developed bearing problems throughout the course of their deployment due to corrosion by moisture, which prevented an accurate wind speed measurement. Apparently water could migrate up the outside of the anemometer shaft under the anemometer cup assembly, and foul the top set of bearings which are not sealed. Although the manufacturer developed a remedy for this problem known as the "Water-Slinger", its use greatly increased the frictional torque required to start the cups spinning. The first modification Lincoln made was to cut a circular notch near the top of the anemometer shaft. In this notch was seated a black rubber O-ring which effectively acted as a rim or lip on the shaft. Second, a Teflon bushing was added to the hub of the cup assembly which extended down completely over the O-ring. After 7 months in the field in 1984, the bearings were found to still be quite clean and lubricated.

It was also found that the anemometer cups were not held securely in the cup hub assembly and were able to twist so that their faces were not perfectly vertical. The cups are held into the hub with hex-key set screws which, when tightened, press down on the hollow stem coming from each cup. Since the stem is made of aluminum, the act of tightening the screw to secure the cup dented the stem which reduced the tightness of the cups. Once the stem was badly dented, there was no way to securely tighten the cups. To fix this problem, each stem was straightened out and a small (half inch) aluminum plug was inserted into the end to prevent the stem from collapsing. After tightening, the cup assemblies were extremely rigid and there was no tendency for the cups to twist in position.

In low wind conditions, four of the anemometers recorded spuriously high peak wind values. Although the chopper disk was barely moving, the circuitry was detecting a high frequency of light pulses. It is likely that the chopper disk was nearly stationary and positioned such that light was just getting through one of the slots. The light detection circuitry oscillated rapidly between detections, giving rise to the spuriously high values. The manufacturer recommended replacement the "R12" 100KΩ resistor with a 1.0MΩ resistor and the "C5" 0.1 μf capacitor with a 0.01 μf capacitor. This essentially created a low-pass filter in the circuitry and made it less sensitive to the marginal detections that gave rise to the peak wind "chatter". The anemometers exhibiting this problem were all fixed during January 1985, and subsequent tests showed their sampled frequencies to be true.

3.1.2 *Anemometer Calibration*

The M.I.T. Wright Brothers wind tunnel was used to measure two aspects of the sensor performance. The first of these was the "friction velocity" or the overall difference in wind measurement between our sensors and the wind tunnel. The second was the effect of flow angles off-horizontal on the wind measurement. The results of this latter test were quite similar to those published by MacCready (1966) and so will not be discussed here.

The friction velocity of the anemometers was measured to determine the difference (discrepancy) between the true and ideal calibration curves. The output was measured at approximately 3, 5, 7, 15, 20, 30, and 35 *m/s*. There was a systematic, nearly linear increase with wind speed of this discrepancy and it was always positive (Fig. 3). Although there are many possible explanations for this behavior, it is probable that the manufacturer specified flow coefficient of 1.8 m, used in the equation to relate sensor output frequency to wind speed, is slightly too large. Since Fig. 3 shows a linear dependence of the wind speed discrepancy on the actual wind speed (slope ~ .044), multiplication of the flow coefficient by (1-.044=.956), making it 1.72 m, would bring the sensor output into agreement with the wind tunnel speeds. A flow coefficient of 1.7 m is currently being used.

3.2 Wind Vane

The FLOWS wind direction sensor consists of a wind vane mounted on a common cross arm with the anemometer. The wind direction transducer is a sine/cosine potentiometer which provides the orthogonal components of the wind direction vector.

3.3 Relative Humidity Sensor

The relative humidity sensor in the temperature-relative humidity probe is the Vaisala Humicap, a thin film capacitive sensor. The probe is situated on one corner of the weather station inside a vane aspirator, which shields the probe from direct sunlight and provides good airflow over the sensors at most times (particularly important for the thermistor).

3.3.1 *Humidity Sensor Calibration*

The recommended calibration procedure for the relative humidity probe is to use two saturated salt solutions, LiCl and NaCl, to produce known constant relative humidity conditions (12% and 75%, respectively), and to adjust the probe until the output signal matches the actual relative humidity. For indoor use, or for outdoor use in a typically dry environment, this "low-end" calibration may be appropriate. However, for outdoor use in a humid environment such as that encountered routinely in the Memphis area, a "high-end" calibration, requiring in addition the measurement of relative humidity at 97% (K_2SO_4) and an adjustment period of 8 hours, is necessary. With this "high-end" calibration, the relative humidity measurement will be accurate at low and high relative humidities and about 2% too low in mid-ranges. The alternative "low-end" calibration is accurate at low and mid-ranges but gives saturation relative humidities of 120% or greater.

3.4 *Temperature Sensor*

The temperature sensor is a two element precision thermistor. Circuitry is provided in the probe for an output voltage inversely proportional to temperature, accurate over the range from -30 to +50°C, or in the newer probes, from -20 to +80°C.

3.5 Barometer

The barometer used in the FLOWS automatic weather station is a modified version of the Weathertronics 7115 strain gage bridge pressure transducer. A Lincoln built 9V voltage regulator (the best possible from the 12V unregulated battery) is used to supply power. The main drawback with this type of sensor is the strong dependence of output on temperature. To keep the temperature constant, the original users installed a heater next to the sensor, then wrapped it in insulating foam, put that package inside a thermos bottle, and placed the thermos inside a large styrofoam cylinder (Fig. 4). A thermistat was put in line with the heater so that the temperature would remain constant. The problem was that the heater cycle contaminated the barometer output signal as it caused the temperature to change near the strain gage bridge. The heaters were removed and the sensors were replaced in their original insulation before deployment in 1986.

3.5.1 *Barometer Calibration*

Pressure calibration curves were determined for each barometer as a function of temperature and pressure in the NCAR pressure chamber. The temperature of the barometer is now used in real time to convert the signal to engineering units before the data are transmitted to the GOES satellite.

3.6 Rain Gage

The rain gage being used is the "weighing bucket" type, which does not have the high resolution of, for example, the "tipping bucket" variety but is stable even in very heavy rain and can resolve changes in precipitation amounts to within 0.2 mm.

4. MESONET HARDWARE

The mesonet tower is a self-guyed, free standing structure capable of withstanding 50 m/s winds and limiting the mast whip to less than ± 5 cm. The mast tips down to allow easy access to the wind sensors and lightning rod. The structure easily supports up to 200 kg and has adjustable legs to provide leveling on uneven terrain. The large foot pads reduce the footprint loading of the tower itself to less than 75 g/cm^2.

The station has an environmental enclosure meeting NEMA Type 12 specifications in which the DCP and the barometer are located (Fig. 4). The NEMA enclosure is itself surrounded and supported by nearly 3/8 inches of steel plate configured in two half-boxes. The battery is stored in the bottom of this outer box.

The solar panels are mounted on the south side of the tripod and are set at a favorable angle for receiving the sun's rays. Two panels are used per station, each containing 36 three inch single-crystal silicon cells enclosed in a weather-proof assembly. The power output is an average of 1.2 amps at 16.2 volts DC. With two panels in parallel the peak power provided is nearly 40 watts. A heavy duty maintenance-free battery designed for cycling applications is trickle-charged continously during daylight hours by the solar panels. The battery provides 105 amp-hour capacity which could power a typical station for about two weeks without charging.

The lightning protection consists simply of an aluminum rod, mounted at the top of the station and wired to a ground rod buried near one of the tripod footpads. The lightning rod can be seen in Figs. 1 and 2 between the anemometer and wind vane at the top of the wind sensor mast. Additional lightning protection has been added to the sensor interface module on the DCP (see section 5.3 below).

5. DATA COLLECTION PLATFORMS

The data from the meteorological sensors consist of analog voltage signals or, in the case of wind speed, of frequency outputs which need to be sampled, averaged, scaled, stored, and finally transmitted to the GOES satellite. All of these functions are performed by the Synergetics 3400 series Data Collection Platform (DCP) shown in Fig. 4. The system being used in FLOWS automatic weather stations consists of a sensor interface module designed specifically for meteorological sensors, a communications module that relays the digitally encoded data to the satellite, and a microprocessor-based control module that regulates the collection, conversion, and transmission of the data. Each module is described in somewhat more detail below.

5.1 Control Module

The control module is basically a programmable general purpose microprocessor (MC6802) that controls the overall workings of the DCP and the data processing. The DCP can be programmed in a high-level language to execute the fairly complicated equations needed to convert the sensor voltages into engineering units, and to perform lower level operations such as system timing control and bit manipulation. Any RS-232 terminal can be used to program the DCP through the serial port on the front panel. Power (5V DC) is available on this port for the portable terminals used in the field.

5.2 Communications Module

The GOES transmitter module can transmit on all 266 domestic and international channels (frequency range 401.7010 - 402.0985 MHz). These channels are software selectable so that the transmitter module need never be opened. The unit has a built-in monitoring system that can provide performance information such as forward and reflected RF power, selected frequency channel, and various other status and error flags. Data are transmitted in the NOAA NESS self-timed operational mode in binary format. Each transmission automatically begins with the required preamble for carrier acquisition, bit synchronization, and frame synchronization. The module supports both long and short preamble formats; the FLOWS weather stations use the short preamble.

5.3 Sensor Interface Module

The sensor interface module is a general purpose interface for a wide variety of sensors. The sensor inputs (screw terminal connectors) can be set up to measure analog AC or DC (single-ended or true differential) voltage signals, digital signals, and frequency signals from 0.125 Hz to 65 KHz. The interface module contains outputs that can be used to control processes, turn on sensors, and supply sensor power. Regulated reference voltages of 1.25V and 5V, each with 10mA of current, are available to power the sensors.

Small gas discharge tubes were added to all the I/O lines on the sensor interface to provide additional protection against lightning damage. Any strong surge that travels along the sensor input lines will ionize the gas in the tubes and break the connection, preventing damage to the electronics. When this does occur, the site must be visited to replace the blown gas tube.

6. TRANSMITTED DATA

Each mesonet station transmits data twice each hour, 24 hours a day. For each of the 7 meteorological variables (both peak and average wind speed are included), there is one 3-byte binary encoded 16-bit data value generated per minute. Thus, 633 bytes of data alone are transmitted (30 min x 7 variables + DCP status word x 3 bytes). Each group of 30 sensor data values must have a one-byte header, and these plus the data plus the required short preamble and final end of transmission character take 52.8 seconds to transmit at the GOES established rate of 100 baud. This allows an interstation gap of 7.2 seconds each minute before the next transmission begins. Since there are 30 stations in the network, a transmission is taking place every minute.

The variables transmitted by the FLOWS automatic weather stations are listed in Table 1. The data units and the DCP sensor sampling times are given as well as the "digital resolution" of the data. The digital resolution is the engineering units equivalent of the sensor output resolvable with the 13-bit A/D converters in the DCP sensor interface. For all sensors except the barometer the digital resolution is not a limitation; the barometer output signal is so weak with 9 V excitation (5-15 mv differential) that the final resolution of the pressure data is 0.2 mb.

The wind direction itself is not transmitted but the information necessary for its calculation is. The wind vane output consists of both the sine and the cosine of the wind angle, thus determining the angle unambiguously. However, there is not time to transmit both signals. Instead, the sine is transmitted when the winds are from the north or the south, and the cosine is transmitted otherwise. The changes occur at 45°, 135°, 225°, and 315°. In this way, the transmitted signal is always in the middle of its possible voltage range, and a 1 mv discrepancy will result in an error of only 0.04° at worst. The signal that is not transmitted is tested to determine whether it is positive, negative, or equal to zero so that the wind direction may be unabmiguously determined. Codes are added to the transmitted data to signify the results of the test.

7. PERFORMANCE EVALUATION

Many different aspects of the weather station network performance evaluation are given by Wolfson, *et al.* (1986); here a simple measure of the operational reliability and data quality is presented. The mesonet missed transmissions are evaluated by assuming that data would be available for every minute of every day from each of 30 stations if no transmissions were missed. Fig. 5 shows the total average percentage of data missing for the network (all sensors) as a function of day of the year for 1984. Two curves are shown: the lower curve represents the percentage of raw data missing and is relevant to the evaluation of operational reliability, while the upper curve represents the percentage of data missing after the final editing steps have been performed. The difference between these curves reflects the overall quality of the data recorded. For the entire 1984 season, an average of only 2.1% of the data were not recorded.

This compares quite favorably with other operational and experimental mesonet systems, and this average has actually been reduced in the two subsequent years. The mesonet sites had to be visited for repairs less than once a month on average in 1984.

ACKNOWLEDGEMENTS

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NOTICE

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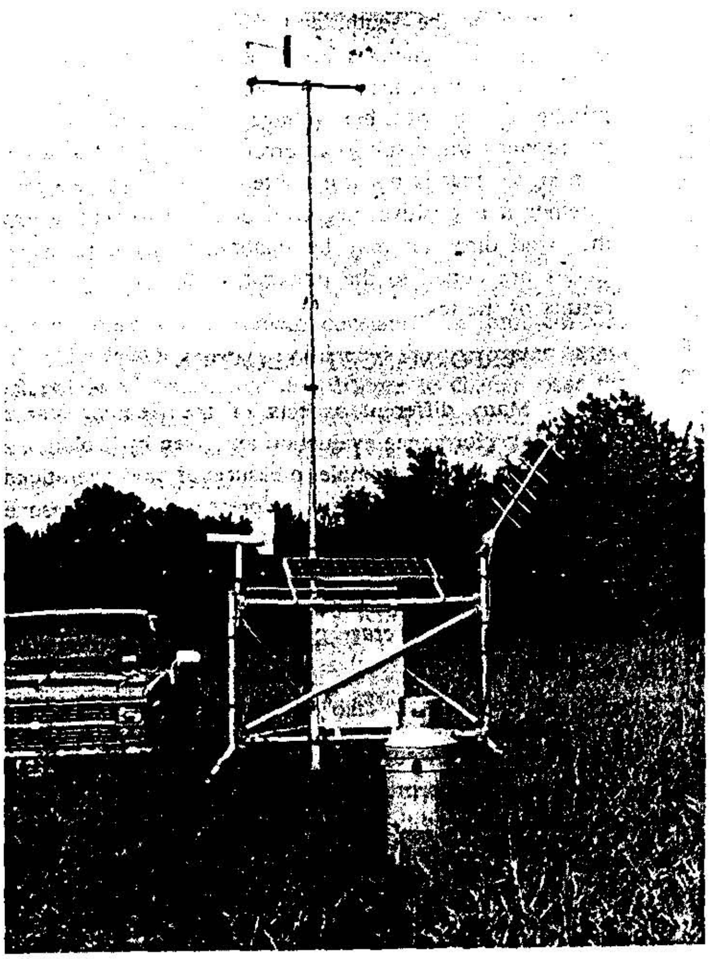
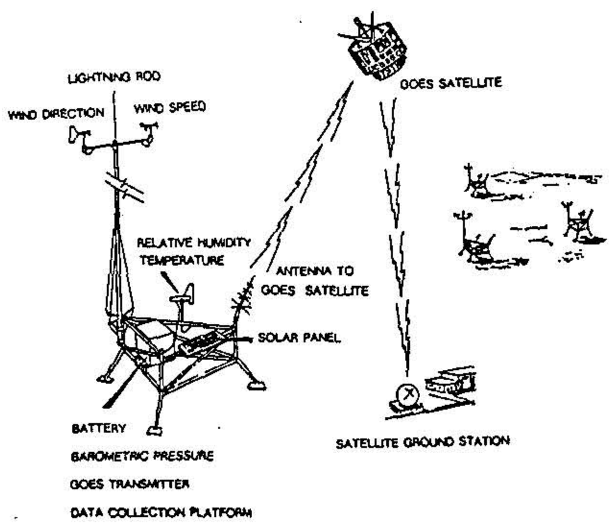


Fig. 1 (left). View of FLOWS automatic weather station in the field. Solar panels are visible above white armored box. Vane aspirator is on the left corner (white tube with fin) and the antenna is on the right. The rain gage is visible in front. Notice that the wind sensor mast is self-guyed.

Fig. 2 (below). Schematic illustration of automatic weather stations in operation. (After Harrison and Hightower, 1982).

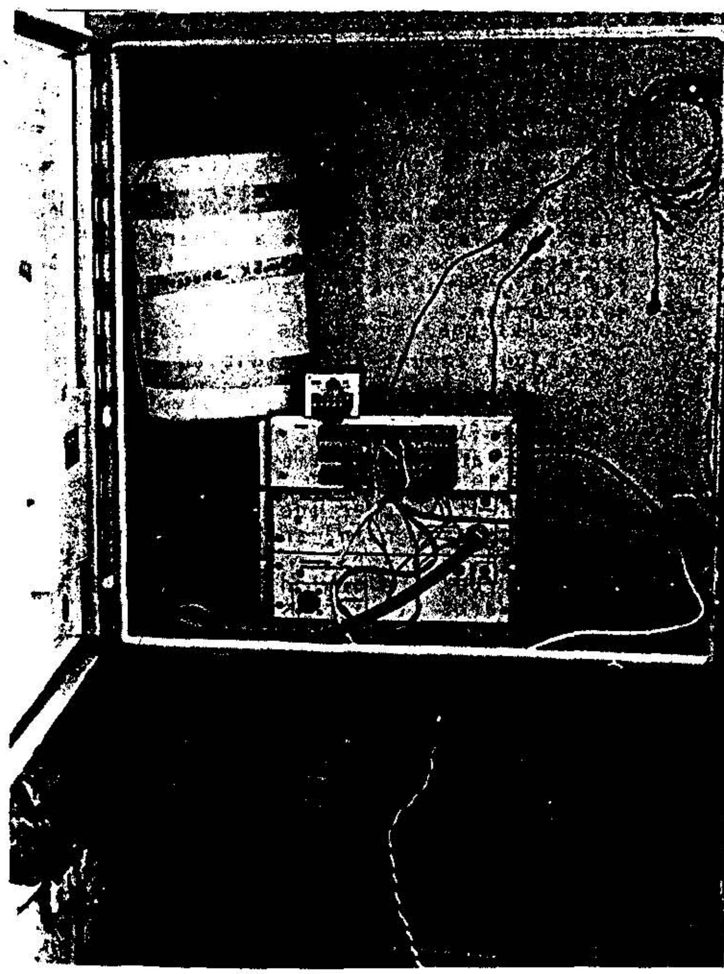


VARIABLE	SENSOR	MANUFACTURER	RANGE	RESOLUTION	DIGITAL RESOLUTION	TRANSMITTED UNITS	SAMPLE TIME
wind speed	cup anemometer	Meteorological Research Inc. (MRI) Model 1022	0.2-54 m/s	0.05 m/s	0.02 m/s	m/s x 100	5 s
wind direct.	wind vane	Meteorological Research Inc. Model 1022 (with sin-cos)	0-360°	0.4°	0.04°	millivolts	5 s
relative humidity	thin-film capacitive sensor	Weathertronics Model 5121-99 (Vaisala HMP-14A)	0-100%	2%	0.02%	% x 100	10 s
temperature	2-elem. thermistor	Weathertronics Model 5121-99 (YSI Sensor)	-30 to 50°C	0.1°C	0.04°C	°C x 100	10 s
pressure	strain gage bridge	Weathertronics Model 7115	900-1100 mb	0.1 mb	0.2 mb	mb x 10	10 s
precip	weighing bucket	Belfort Instr. Co. Model 5915R	0-300 mm	0.2 mm	0.1 mm	mm x 10	10 s

Table 1. Measurement specifications and variables transmitted by the FLOWS automatic weather station network.

Fig. 3 (below, right). Plot of the difference between anemometer measured wind speed and tunnel (Baratron) measured wind speed (Discrepancy) versus tunnel measured wind speeds. Overspeeding of the anemometers always occurred.

Fig. 4 (below, left). White armored box containing environmental NEMA enclosure and battery is shown. Inside the NEMA enclosure, the barometer (pressure transducer) and the DCP can be seen. The Lincoln-built voltage regulator is the small box on top of the DCP (provides 3.6 V to humidity probe and 9V to barometer).



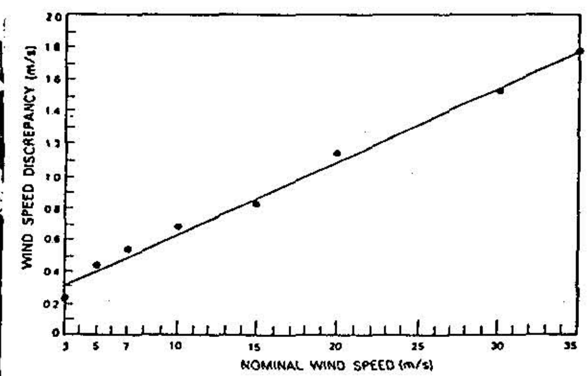


Fig. 5. Total average percentage of data missing for the FLOWS Memphis network as a function of day of the year in 1984. The days on which the network was not operating are shown as hatched regions.