

DEVELOPMENT OF A 2-AXIS SNOWFLAKE IMAGING SYSTEM

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Abstract. *Current attempts to measure snowfall with standard precipitation gauges, snow pillows, etc.; may not provide accurate measurements in most conditions. To validate present remote sensing snowfall accumulation algorithms and future snowfall measurements from the Global Precipitation Measurement mission, an accurate estimate must be obtained. Dr. Larry Bliven of NASA/Wallops Flight Facility (WFF) has developed an instrument capable of imaging raindrops along 1-axis (i.e. x-z or y-z plane). Preliminary experiments imaging snowfall with the 1-axis system indicate that the development of a 2-axis system may be advantageous to producing more accurate snowfall estimates versus the 1-axis system or current snowfall estimation instruments. The exploration into the hardware, software, positioning material and procedure necessary to complete development of this instrument has begun and will be discussed.*

1. INTRODUCTION

a. Snowfall Measurements

Snowfall measurements of any kind are much more difficult than rainfall measurements. This is because snowfall's small bulk density permits it to be affected by the wind much more quickly than rain. Precipitation gauges, like the tipping bucket or the fisher/porter gauge can be severely handicapped in their ability to measure snowfall accumulations. Even with a wind shield in place, these gauges can suffer from undercatchment rates over 50%. Figure 1 shows a plot of the gauge catch ratio of the Universal Precipitation Gauge with a wind shield versus wind speed. Note that as the wind speed at gauge height approaches 7 m/s, or about 16 mph, only about 40% of the actual snowfall is sampled. Using measurements like those in Figure 1 would be devastating to a ground validation mission.

Snow pillows or snow boards can suffer from the same undercatchment issues. Personal experiences with snow boards have shown periods of no accumulation, followed by periods of greatly increased accumulation with

steady snowfall rates. These effects are due to drifting of the snow by the wind.

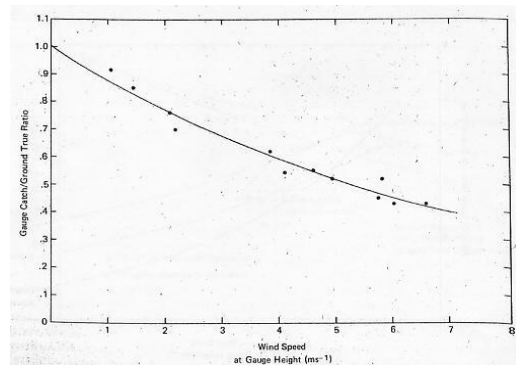


Figure 1: Gauge/Actual ratio versus wind speed (m/s) for the universal precipitation gauge. Courtesy of Goodison (1978).

Another concern when using a snow pillow or snow board are the density estimates generated from them. A core sample is generally taken off the snow board and weighted to establish the Snow Water Equivalent (SWE). These estimates could be much larger than the actual density of the falling snowflakes due to compaction on impact and in wind generated drifts. If used in algorithms either by ground or space borne

radars, they will have a significant impact on that radar's estimated SWE accumulation.

b. Rain Imaging System

Dr. Larry Bliven of NASA/WFF has developed an instrument named the Rain Imaging System (RIS), which is capable of imaging rainfall and producing size distributions of the drops imaged. The instrument consists of three parts: the optical system, the PC data logger, and analysis software on the same PC or a different one. The optical system consists of a grayscale digital camera with a 100-300 mm zoom lens adjusted so the focal plane is 2 m from the lens. The camera is encased in a watertight security camera housing. The light source contains a 300 W bulb placed approximately 3.5 m from the front of camera housing providing the necessary illumination of the particles in the sample volume.

The sample volume for rain imaging is 32 mm wide by 24 mm high. The depth of field is dependent on particle size and Dr. Bliven has developed a relationship for rainfall. The relationship, using an f-stop of 8, is given by:

$$DoF = 115 * D \quad (1)$$

where DoF is the Depth of Field (mm) and D is the diameter of the particle (mm). A DoF relationship for snow is the subject of ongoing research. The image resolution is 640 by 240 pixels, which results in a pixel size of 0.05 by 0.1 mm with the aforementioned sample volume size. The camera transmits 8-bit grayscale images at a rate of up to 60 frames per second.

A picture of a RIS deployment is shown in Figure 2. The design of the RIS minimizes the interference of the instrument on the sample volume caused by wind. The only time this instrument will cause turbulence in the sample volume is a strong wind blows nearly parallel to the line of sight of the

camera. This is the most important advantage of the RIS.



Figure 2: Image of the RIS near Grand Forks, ND.

The minimal wind interference permits the instrument to sample undisturbed hydrometeors. Other optical disdrometers like the 2-D video disdrometer (2-VD) and the Particle Size and Velocity (PARSIVEL) may well suffer from wind interference to a much greater degree than the RIS. A personal communication from Dr. Paul Kucera, noted that the 2-VD under samples snowfall even in light wind situations. The PARSIVEL looks similar to a miniaturized RIS. However, its sample volume may be too close to the housing, suggesting it may be susceptible to wind induced errors as well.

Dr. Bliven has developed the acquisition and processing software for the RIS in the LabView software suite. The acquisition software begins by initializing the video stream from the camera and proceeds to take 128 images to determine the average background. The average background information is used to normalize the background to all white. When these steps are completed the actual processing of images begins.

First, each image is run through a preliminary threshold process to determine if there are dark pixels in the image. A threshold process uses a user-defined value to decide if a pixel is black or white. Because these images are 8-bit unsigned integers the

pixel values can range from 0 to 255, with 255 being all white and 0 being all black. Thus, if the user chooses 200 as their threshold value, a pixel with a value above 200 is considered white and below 200 is black. Images with black pixels are then compressed and stored into hourly data files with frame count and timestamp information. Because of the normalized background, hydrometeors falling into the sample volume have a large contrast with the surrounding pixels, permitting this initial threshold technique to successfully identify all particles in the sample volume.

The processing algorithm reads the hourly data files and recreates the stored images. An edge detection algorithm is employed to determine particle size. Edge detection uses the gradient of the image to determine where an edge is located. Relevant particle information is then deduced using various LabView image analysis functions and output to hourly tab delimited text files. Further processing can be done with these files to produce size distributions, accumulation rates, radar reflectivity factors, etc. A viewer program is also available to view and save images of interest.

c. RIS Results

During the winter of 2003-2004, a RIS was deployed near Grand Forks, ND. The RIS was able to operate flawlessly in the harsh conditions of Eastern North Dakota. Periodic maintenance included removal of snowdrifts, data transfer to DVDs and alignment checks of the light source.

On 25-26 January 2004 a snow event produced around 14" of total accumulation at the NWS Forecast Office in Grand Forks. This event was captured in entirety by the RIS. In conjunction with the RIS core samples were taken in a sheltered area to give an approximate density value for the falling snow. Crystal type observations were also performed and published density relationships (Magono and Nakamura 1965, Pruppacher

and Klett 1997) were used along with the core sample density estimates in the calculations completed. Figure 3 shows a sample image taken from the RIS during this event.

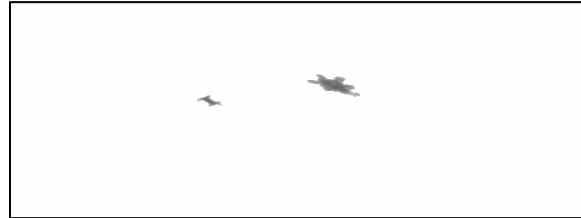


Figure 3: This is an example grayscale image from the RIS from 25 January 2004. Notice the capped column and the dendrite. This indicates crystal formation in different locations of the cloud.

Using the particle sizes determined by the processing software, density relationships described earlier and published terminal velocity relationships (Heymsfield 1972); size distributions were generated for equivalent spherical ice balls. These distributions were then used to calculate radar reflectivity factor and SWE rate at 6 min intervals for the entire event. Figure 4 shows an example size distribution of the actual snowflakes, before the determination of the ice spheres using the above technique.

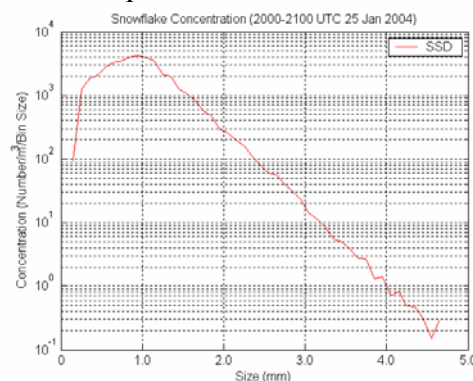


Figure 4: Number concentration (number/m³) versus diameter for snowflakes from 2000-2100 UTC 25 Jan 2004. The large decrease in concentration at small diameters is possibly an artifact of the processing algorithm.

Reflectivity and SWE rate calculations were produced every six minutes in order to correspond with the scanning strategy of the

Mayville, ND Doppler Weather Surveillance Radar (KMVX). Comparisons of reflectivity from KMVX and the RIS SWE rates were made to generate a Z-R relationship for KMVX based on RIS measurements. This method is similar to that of Fujiyoshi et al. (1990). The Z-R was used to estimate the storm total SWE accumulation over Grand Forks. This estimate was then compared to the estimate using the NWS snowfall accumulation and the snow core density estimates, which was taken as the “truth”. Figure 5 shows the reflectivity to SWE rate plot used to determine the Z-R. When the storm total SWE accumulation was produced from KMVX the result was 15 mm while the total using ground measurements was 27 mm. This gives an 80% relative error.

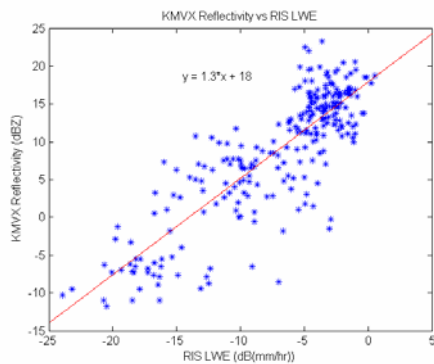


Figure 5: Scatter plot of KMVX reflectivity versus RIS LWE (mm/hr) in dB space. The given equation is the least squares linear fit to the data produced in Matlab.

There are several sources for error in these calculations, one of which is the density and size estimate of the snowflake. When using the RIS, only the maximum size of the snowflake in either the x-z or y-z plane can be determined. There is no ability to observe variations along the x or y-axis and the axis coming directly towards or away from the camera. This leads to sizing errors in both the LabView functions and the equivalent ice spheres.

Using published density estimates can give a close estimate for the density of a certain crystal type in certain conditions.

However, crystal types and conditions generally do not match perfectly with those of the given relationships. Crystal type can also vary greatly throughout the course of a storm generating the need for multiple density relationships.

From preliminary comparisons using the snowfall event shown above the RIS reflectivity and SWE rate calculations are very sensitive to density changes. It was shown that a 50% change in density leads to a factor of 4 change in the resultant reflectivity. The development of a 2-axis system may lead to the ability to estimate the actual volume of each snowflake rather than estimate a diameter and assume a shape around that diameter. Using this information with additional measurements may lead to more accurate density estimations. These improved density estimates would aid in the development of improved remote sensing algorithms for SWE accumulations. Crystal habit may also be identified more readily with the 2-axis system, which lends itself to validation of polarimetric radar observations. It is for these reasons a 2-axis Snow Imaging System (SIS) is being developed.

2. SNOW IMAGING SYSTEM

a. System Overview

The SIS uses two cameras placed orthogonal to each other to produce two images of one hydrometeor along both the x-z and y-z planes. This provides more information about a crystal’s shape and gives the maximum dimensions in all directions. With this added information particle habit and shape can be estimated which will give improved estimates of the density of the falling snowflakes.

When aligned properly the two cameras will have an overlap sample volume of 32 mm wide by 32 mm long by 24 mm high. Figure 6 shows an example of the two sample volumes overlapping to create the 2-axis sample

volume located in the center of the two rectangular boxes. The 2-axis sample volume is defined by the bounds of the central box eliminating the need for a Dof relationship.

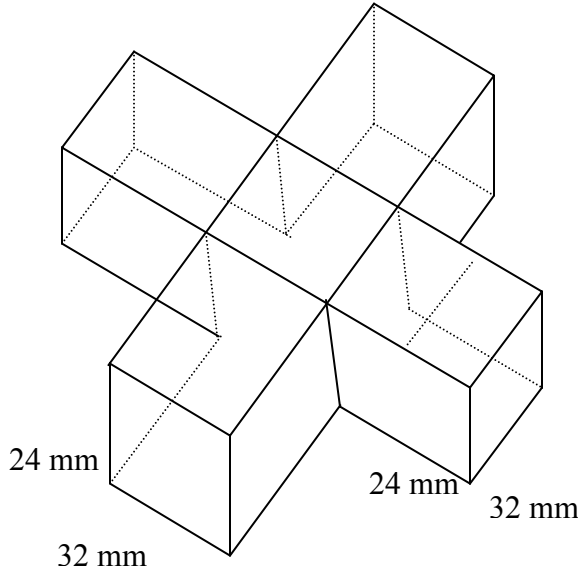


Figure 6. A drawing of the sample volumes from two orthogonal 1-axis RIS systems.

b. System Hardware

Even with the requirement of two cameras, and thus two lenses and two light sources, current computer technology permits the use of one superior desktop to acquire frames from both cameras. Current testing shows that a 3.4 GHz Pentium 4 processor with 1 GB DDR SDRAM can acquire 45-50 fps from both cameras, which is adequate for the SIS's intended purposes.

Choosing the appropriate camera for the 2-axis system requires the camera to perform more functions than in the 1-axis system. To remove blurring of the hydrometeor due to its motion a maximum exposure time of $1/50,000^{\text{th}}$ of a second is required. It is strongly preferred to have an exposure time of $1/100,000^{\text{th}}$ of a second.

An improved resolution was chosen for the 2-axis system. Instead of using a 640 by 240 line image a 640 by 480 line image will be used in the 2-axis system. Using the same

sample volume as in the RIS results in a 0.05mm horizontal by 0.05mm vertical resolution. This will permit improved size and volume estimation as well as the detection of smaller particles.

For these cameras to take images of the same snowflake they must acquire images at nearly the same instant. This requirement demands cameras that can be synchronized through the use of an external trigger, rather than the camera acquiring in its internal mode, as in the RIS. Because of this requirement a new camera had to be selected.

An extensive search through the available cameras and several lab tests of potential units has led us to the Sony XC-HR50 camera. This camera meets all requirements set forth by this project at a reasonable price. To synchronize these cameras, there are two possible routes under consideration.

The first route uses the current camera interface boards, produced by National Instruments (NI) (developers of LabView), used in the RIS. Mounting two interface boards on one computer allows the user to control both cameras. These interface cards will generate trigger signals that can be received by the camera with the purchase of an extra cable for each camera from NI.

Software has been written that generates the trigger pulse in both interface cards and the cameras can acquire frames using the external trigger. This method creates a random offset of several frames due to initialization of the interface boards consecutively. A correction to the frame grabber portion of the acquisition software was created in lab testing and is currently being adapted to be completely autonomous to permit continuous field acquisitions.

The second route requires both interface cards, extra cables for each camera from NI and an external signal generator. Using the signal generator, the trigger pulse is defined and sent to both cameras simultaneously, thus removing the need for the interface cards to

generate trigger pulses and synchronize the sending of those pulses. This route, while adding another item of hardware, removes code development and testing as well as synchronizing the cameras to a more rigorous time interval.

Presently, the 2-axis acquisition program is able to capture triggered, synchronized images from both cameras using the second triggering technique. However, a minor software glitch was discovered in recent testing. This error causes the acquisition program to grab incorrect frames from each camera occasionally creating the illusion of non-synchronized cameras. A solution to this problem is being implemented into an updated version of the acquisition program at this time.

c. System Software

Along with the testing and selection of the appropriate camera the necessary software is under development to acquire, process, and view images, as well as produce distributions and volume estimates from the processed images. Modifications were made to the 1-axis acquisition program so that it initializes two camera feeds, normalizes the backgrounds and compresses two images into two distinct units. Headers differentiating each camera feed are placed at the beginning of each new image unit. These units are then combined into the hourly files, using a similar naming convention. A distinct identifier is added to denote compressed image files that contain information from two cameras.

A similar method was used to create the first of two processing programs for the 2-axis system. Using the RIS processing program as a base additions were made to accommodate a second camera. This program reads the compressed image files and outputs to two distinct tab delimited text files. The fields in these output files are exactly the same as those in the RIS. This allows the 2-axis system to be used as two co-located RISs for

comparison studies or variability studies over very short distances.

The second processing program reads the output of the previous program and determines what crystals are found in the 2-axis sample volume as shown in Figure 6. The program then recreates the necessary images and produces a volume estimate based on the size of each image. Currently the algorithm is summing many small rectangular slices to recreate the actual hydrometeor, which can give up to a 40% relative error when the actual shape is spherical or cylindrical. By using shape assumptions, further refinement of this algorithm will be made. Using both images to determine crystal habit and thus a predefined shape will permit the summing of more accurately defined slices reducing the 40% error significantly.

Figure 7a,b shows two raw images of drops created in a lab setting. These images were taken from the Sony cameras using the second synchronization method discussed in section 2b. These images would then be processed with both processing algorithms to produce size and volume estimates of the drops.



Figure 7a. Image taken from camera 1. Looking east to west.



Figure 7b. Image taken from camera 2. Looking south to north.

To assist in the development and validation of the two processing programs a simple hydrometeor simulator has been developed. This simulator uses an exponential distribution of the form:

$$N_o(D) = \Lambda * e^{D\mu} \quad (2)$$

where $N_o(D)$ is the number concentration per m^3 , and D is the hydrometeor diameter in mm. The user can define Λ (y-intercept), μ (slope parameter) and the number of drops to simulate from the defined distribution.

The simulator has a 1 in 5 chance of placing a drop in each frame. This is done in an attempt to simulate the absence of particles in some frames during precipitation. If a particle is to be entered into the upcoming frame the simulator randomly picks one of the two cameras and one of five distance locations in that camera. The camera's sample volume was broken into five sections because the 3.2 mm long overlap sample volume is approximately 1/5th of the total sample volume for each camera. Therefore it is possible that if a hydrometeor falls into a camera's sample volume it has a 1 in 5 chance of being in the 2-axis sample volume.

When it is determined that a particle should appear in a frame, what camera it will appear in and where the simulated particle is created in the image, it is stored in the same manner as the actual field acquisition program. Particles that fall into the overlap area are written to both cameras' frames.

The hydrometeor simulator can easily recreate raindrops and geometric shapes (ie. squares, rectangles). These simulations will be used to validate the two processing programs. Lab tests have shown that the initial processing program keeps all information deemed to be part of the hydrometeor and the secondary 2-axis processing program can produce rough volume estimates of spherical drops. Future improvements to the simulator will include the

development of snowflake shape simulations and incorporation of the finer details of precipitation and the acquisition program's output to more accurately simulate natural observations.

d. Mounting hardware

Two possible camera mounting stands are under consideration. Both use material found at local home improvement stores with minimal or no special fabrication needed, making the mounting relatively easy and low cost. The first platform begins with an 18" by 18" by 4" thick concrete slab with three to six 3/4" threaded rods placed into the concrete. A flange, attached to a three foot section of schedule 80 10" outside diameter PVC, is then bolted to the threaded rods. While schedule 80 PVC is less common, it was selected because the wall thickness is over 0.60" when using a 10" diameter pipe. This gives much needed rigidity to the stand.

Another flange is attached to the top of the PVC section. A 1/4" thick aluminum disk approximately 16-18" in diameter is mounted to the top flange with six bolts. The mounting points in the aluminum disk will be slotted to provide angular adjustment (left/right) of the camera. Also, the actual mounts will be height and angular (up/down) adjustable. Attached to the aluminum disk, in four places, is the camera housing with the camera mounted inside. The camera may be mounted on a vibration damping material, Sorbothane, if wind vibrations are noticeable. This material attempts to isolate the camera from the stand giving an undisturbed image.

The second podium begins with a 6-10" diameter, 1/4" walled, steel tube 3-4' in length. This will then be welded to a square section of steel, again 1/4" thick. At the mid point of the pipe four mounting brackets will be welded. From these brackets, four sections of galvanized angle iron will be bolted. From the steel base, four more sections of galvanized angle iron will be bolted and run to the angle

iron attached to the pipe mounting brackets. Lastly, four lengths of angle iron will be bolted between the four braces. This will create a square on the ground with four pieces of angle iron running into the central mounting plate for the steel pipe, and four segments rising up to the mounting brackets. A flange will be attached to the top of the steel pipe and the mounting of the camera will be the same as in the first stand.

The first camera mounting system is easier to construct and cheaper. However, it may not be as resistant to wind vibrations as the second mounting system. The second system will require several welds and the ability to galvanize those parts when welding is complete. This increases cost and time required for assembly. Over the next twelve months assembly of one or both of these camera mounting systems will be performed and their performances will be assessed. The light source mounting will be the same as in the 1-axis system. It consists of a shop light tripod available at any home improvement store. A 150W or 300W bulb is placed into the housing provided with the tripod. The only modification to the purchased lighting structure is frosting the glass pane through sand blasting. This provides more uniform lighting in the sample volume.

Emphasis has been placed on developing a system that is transportable, easy to assemble and low cost and low maintenance. With the two suggested mounting configurations these goals appear to be met. Lab and field testing will provide insight to any modifications needed and will be completed by fall 2005.

e. Procedural Overview

The procedure to successfully deploy a SIS contains several steps. The first is finding the site location. The SIS presently needs access to A/C power and a location to house a PC. The length of the power extension and video cables limits the camera placements to roughly 100 feet from the PC. Thus a site

with A/C power and a level unobstructed area around the PC placement location is needed. Once the site has been chosen, select the location for one of the two cameras. Assemble and place the camera, measure 63" from the end of the camera lens and mark that location. This is the location of the focal plane for the SIS. Measure 63" orthogonal to this mark. This is the location of the end of the second camera lens. Assemble and place the second camera. The light assemblies should be placed 34" behind the focal planes of each camera. Connect the video and power cables to the power supply and PC.

After the rough alignment is complete start NI's Measurement and Automation (MAX) program to view images from either camera. By placing an object at the intersection of both focal planes, one can adjust the height and angles of the camera so that the object is centered and focused in both sample volumes. Align the top edge of the object with the top edge of each camera. Following the camera adjustments, correct the light placements so the images are as light as possible. Do this by using the histogram available in MAX and maximizing the lowest pixel value.

The acquisition and processing software has a minimal amount of documentation associated with them, and efforts are being taken to create a more detailed procedure regarding their use along with improved code documentation. A more detailed procedure for the SIS location, setup and alignment will be written after several field placements are completed.

3. FUTURE WORK

Over the next twelve months, completion of the 2-axis SIS system should occur. Selection of the triggering method and rigorous testing in a lab setting will be performed before field placement. A final mounting system will be chosen and fabricated. This will be tested in lab and preliminary field experiments and any

necessary modifications will be made. The materials list and procedure for assembly and field placement will be documented.

Software improvements will continue to be made through use of the hydrometeor simulator. The simulator itself will also be improved to better approximate natural precipitation and include more realistic shapes of snowflakes. Using these advanced replications, further validation of the first processing algorithm will be performed. The second processing program, the volume estimator, will benefit greatly from the simulated snowflakes. This algorithm is presently very basic and experimentation with known shapes and volumes must be executed to validate it.

Along with the continued development of the 2-axis system further research will be conducted with the RIS to improve the understanding of how snowflakes are imaged. RIS systems will also be used to assess new camera and data transfer technology. This will result in more accurate and robust 1 and 2-axis systems.

4. CONCLUSIONS

With the use of the RIS, preliminary work has shown the instrument capable of functioning in the harsh environment of North Dakota. Analysis of the recorded data illustrates that the RIS gives realistic measurements of snowfall. The uncertainties in snowfall density, terminal velocity and sample volumes are being investigated. Techniques are available to decrease the uncertainty of these supplemental measurements using the RIS and other instruments. However, the advent of a 2-axis system may enable us to further decrease the uncertainty of snowfall density, and significantly reduce sample volume uncertainty through the elimination of the DoF relationship.

During the past three months the initial evaluation of hardware was performed. The

camera was chosen based on system requirements and is currently the Sony XC-HR50. Lab tests have shown that the external trigger signal can be generated and the camera responds correctly to both methods. Either of these triggering systems is capable of being placed into a field setting, but it is not yet known which method is most easily implemented and robust.

Software has been developed that is capable of acquiring images from two cameras. A software glitch in the selection of the current frame has been identified and a solution is being developed. Two processing programs give the ability to produce distinct output from each individual camera or obtain volume and shape estimation of particles in the 2-axis sample volume. A hydrometeor simulator lets the user randomly place particles from an exponential distribution into the sample volumes of the 2-axis system. Further improvements to the simulator will lead to advanced processing techniques without the need for actual data.

Initial designs of the mounting apparatus have begun and two design possibilities are under consideration. Each one has the ability to perform the necessary task. An experimental production of both systems will be done to highlight any production difficulties and total expenditures. Lab testing will provide evaluation as to which system is best suited for placement in the field.

Overall the initial development of the 2-axis SIS system has been difficult but significant progress has been made. A deeper understanding of the hurdles yet to be overcome gives confidence that the 2-axis SIS will be successfully developed and deployed in the near future, as a relatively low cost, robust and easily maintained video disdrometer.

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