IMAGING SYSTEMS FOR AUTOMATED 24-HOUR WHOLE SKY CLOUD ASSESSMENT AND VISIBILITY DETERMINATION

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ABSTRACT

A family of ground-based, passive image systems has been developed for assessment of the environmental state of the atmosphere. The primary cloud system, the Whole Sky Imager, measures cloud cover, and cloud free line of sight over the upper hemisphere at 1/3 degree spatial resolution. Several of these systems have been fielded for 2-3 years, acquiring imagery every minute under automated control. A related system, the Horizon Scanning Imager, makes determinations of horizontal line of sight visibility in all sectors. Both of these systems are currently undergoing development to extend their capabilities into the night-time regime. This paper discusses these systems and their applications, ranging from military applications to support of global warming research and satellite ground truthing.

1. INTRODUCTION

In recent years the Marine Physical Laboratory of Scripps Institution of Oceanography has developed and fielded several imaging systems for assessment of the cloud field dynamics, as well as for visibility determination. The Whole Sky Imager (WSI) images the sky dome and identifies cloud distributions, from which earth-to-space cloud free line of sight and cloud free arc determinations may be made. This development was driven by the need for a ground-based determination of high spatial and temporal resolution cloud dynamics. The system has been used both for direct operational support, and for support of the modeling community. Similarly, the development of the Horizon Scanning Imager (HSI) was driven by operational requirements for an assessment of the optical attenuation through the atmosphere along horizontal lines of sight. This paper gives an overview of the daytime systems, and discusses the current development toward full 24-hour, day/night capability, as well as the applications, both military and civilian, of these systems.

2. WHOLE SKY IMAGERY FOR CLOUD ASSESSMENT

2.1 OVERVIEW OF THE DAYTIME WSI SYSTEM

The Whole Sky Imager is a passive, ground-based sensor. It uses a fisheye lens to acquire images of the upper hemisphere down to an 80 degree zenith angle. A combination of spectral and neutral density filters, in conjunction with a Charge Injection Device (CID) solid state camera, enables acquisition of images which may be fully calibrated radiometrically. The sensor is controlled automatically, with four images acquired every minute, at 512 x 480 resolution. This yields 1/3 degree spatial resolution, for a footprint of roughly 17 meters for a cloud layer at 3 km altitude. The system is controlled by an IBM AT-clone with a resident 2.2 Gbyte tape system for data archival. In the field, the current system acquires data every minute, for 12 hours a day. A new tape must be inserted once a week for continuous operation. The system is further discussed in Shields, 1990a, and Johnson, 1989.

Following archival, data tapes undergo an automated process to yield cloud decision tapes, in which each picture element (pixel) has been identified as opaque cloud, thin cloud, or no cloud. Data which are not valid due to conditions such as offscale dark are also identified and so labeled. In this procedure, the image undergoes several processing steps. A number of calibration corrections are applied, to account for slight sensor non-linearities, filter passband differences, neutral density spectral bias, and so on. The images acquired at 650 nm and at 450 nm are ratioed, to remove most of the directional and temporal variation in the background sky radiance. In the remaining ratio image, opaque clouds are identified by a fixed ratio threshold. Optically thin clouds are identified as a fixed perturbation with respect to the background sky ratio. This background sky ratio varies from pixel to pixel, as well as image to image, to allow for changes in aerosol load and changes in ratio due to different look angles and solar zenith angles. This process is further discussed in Koehler, 1991.

A sample cloud image is shown in Fig. 1 with the final cloud decision image in Fig. 2. In this black and white version of the normal color cloud decision display, those pixels which are automatically identified as clear appear dark grey, and those identified as thin or opaque cloud are light grey to white. The center of the image is the zenith. The square black object is the sun occultor, for stray light control, and the other black regions are objects in the field of view that have been masked (most sites do not have any undesired objects in the field of view).

The systems have performed quite well in the field over the last three years. A data base of approximately 900 Gigabytes of raw image data (approximately 4600 data days) has been generated. Of this data, 14 months at each of 4 stations have been processed to the cloud decision image (Johnson, 1991b, and Ciandro, 1991). The results compare quite well to the standard observer (Shields 1990a, and Koehler 1991).

2.2 THE DAY/NIGHT WSI

The new Day/Night WSI will take advantage of many of the technologies that have been used in the current WSI. The sensor schematic is shown in Fig. 3. The new system includes a larger fisheye lens, for full upper hemisphere coverage down to 90 degrees zenith angle. This

Figure 1. Raw Data Image. This image has been acquired using a red (650 nm) filter with the WSI.

Figure 2. Cloud Decision Image. Each pixel location has been identified as opaque, thin, or no cloud by an automated algorithm applied to WSI imagery.

should enable detection of the vertical buildup on the horizon, as well as providing full coverage for comparison with the meteorologica observer.

The Day/night WSI uses a slow scan Charge Coupled Device (CCD) sensor to yield the additional sensitivity required for nigh operation. Spectral filters will be used, as with the Day WSI, at least down to quarter moon conditions. A fiber optic taper is used in place of the previously used lens relay system, to resize and relocate the image plane. The Day WSI's equatorially driven solar occultor is being replaced in the Day/Night system with a zenith/azimuth dual drive occultor, in order to more readily transition from sun to moon occultation and adapt to use on moving platforms.

The Day/Night WSI hardware block diagram is shown in Fig. 4. Conceptually, this system is quite similar to the Day WSI, althoug there are some hardware changes to both the sensor and the controller end, necessitated by the required compatibility with the new camera This system will be fully automated, under control of an IBM AT clone, just like the Day WSI.

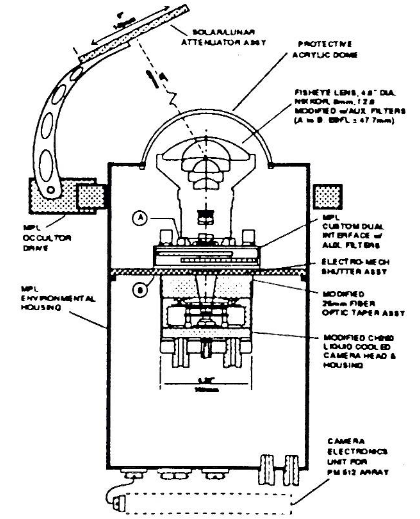

Figure 3. Day/Night WSI Imager Assembly. The system uses a 180 degree fisheye lens, slow scan camera, and custom filter and occultor assemblies.

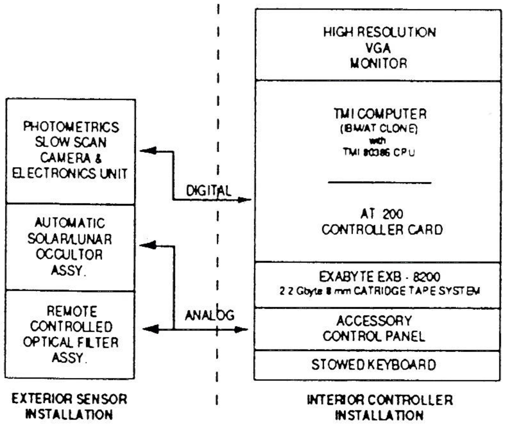

Figure 4. Day/Night WSI Hardware Block Diagram.

One of the important design criteria is the large range of flux levels the system must be able to deal with. Figure 5 shows the naturally occurring illuminance levels under a variety of lighting conditions. These data are from the work of Brown 1952, and are consistent with irradiance measurements acquired by our group at the Visibility Lab over a period of several years. In Fig. 5, the daytime illuminance conditions the Day WSI has had to deal with are shown in the top two curves on the right side of the plot. These represent clear to dark storm conditions for sun zenith angles 0 to 90 degrees. The Day/night WSI should be operational at least down to quarter moon conditions shown on the bottom right curve, and hopefully down to the starlight conditions shown on the left side of the plot. This represents approximately a 9 log range of lighting conditions. The sensor is designed to obtain the necessary sensitivity range by using the approximately 3-4 log sensitivity of the camera chip, 2-3 logs range from exposure control, and 2-5 logs range through neutral density filter control.

A sample night image and its histogram are shown in Figs. 6 and 7. This image was acquired under starlight (no moon) conditions, in the city of Tucson. This test image was acquired with a limited field of view, and is thus not in the final WSI format. However the clouds are clearly discernable, as are the clearer areas of the scene.

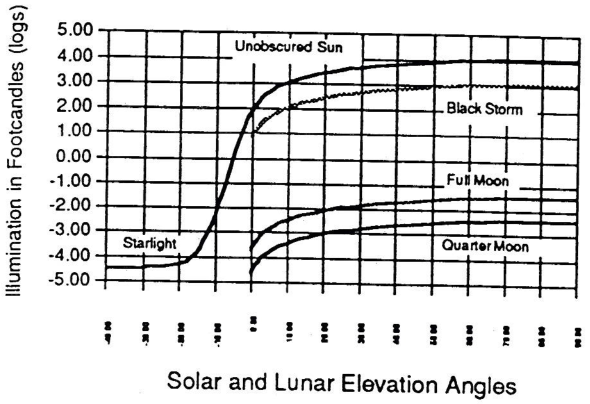

Figure 5. Natural Illumination Levels. These measurements, from Brown 1952, illustrate flux conditions the Day/Night WSI should encounter.

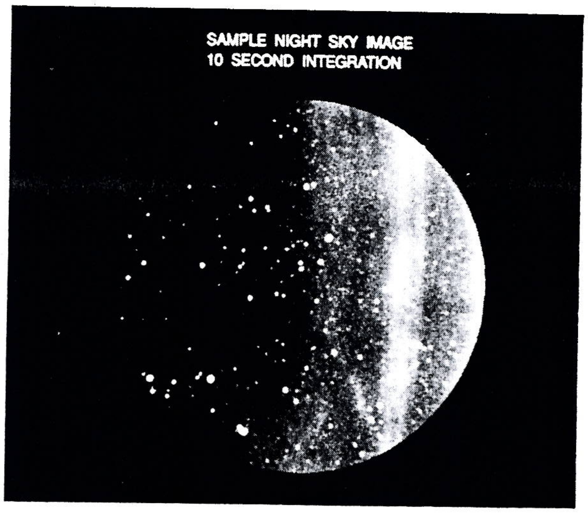

Figure 6. Sample Night Sky Image. The image was acquired at 10 seconds integration with the slow scan camera, and a limited field of view lens.

In the histogram, the first spike at the low end is an artifact of the baffle used (the baffle has been masked in Fig. 6). The region of interest is represented by the second spike in Fig. 7. Note that due to the large radiometric range of the camera, the sky and cloud radiance is a relatively small portion of the range; this large range is convenient for automatic flux control. The CCD camera has low noise and a 16 bit readout, which means that the system retains a good radiometric resolution, as required to bring out the details of the cloud scene. This combination of high resolution, large range, and high sensitivity with outstanding image quality was important in the selection of the basic sensor.

For moonlit images, it should be possible to use a cloud decision algorithm which is conceptually similar to that used in the Day WSI. A study of night radiance distributions acquired by our group in 1968 and 1969 has been made to evaluate the red/blue ratios under a variety of conditions (Gordon, 1989). This study indicates that down to quarter moon, the red/blue ratio should be a reasonably good indicator of clouds, but for starlight conditions the spectral character of the sky is quite different, and a different algorithm will probably be required.

3. HORIZON SCANNING IMAGER FOR VISIBILITY DETERMINATION

3.1 OVERVIEW OF THE DAYTIME HSI SYSTEM

The Horizon Scanning Imager (HSI) is designed to determine the visibility, or the attenuation due to the aerosol load, over horizontal lines of sight. Even in the absence of clouds, there are many military systems which are impacted by the optical attenuation of the atmosphere. This system enables the determination of this loss, as characterized by the visibility, over horizontal paths in all directions.

The HSI scans the horizon, acquiring a set of images such as that shown in Fig. 8, at several azimuth look angles. Dark targets are previously identified in the scene at a variety of ranges. The contrast of each of these targets with respect to the horizon is measured radiometrically by the HSI, and used to compute the visibility automatically.

Figure 9 illustrates the decrease in the contrast of a black target with respect to the horizon, as range to the target increases. Note that the apparent contrast, i.e. the contrast as measured from the given range, decreases exponentially. This rate of decrease depends on the attenuation of the atmosphere. Visibility is defined as the range at which this contrast decreases to the human contrast threshold, taken to be .05 in this illustration.

The lower curve of Fig. 9 shows the apparent contrast of a sample target which is not perfectly black (inherent radiance not equal to 0). The HSI is able to measure the contrast of non-ideal targets such as represented by the lower curve, at a variety of ranges, and mathematically determine the visibility. This technique has several advantages over visual determination of the visibility: it can use targets which are not black, which are not at the range equal to visibility, and which are not physically adjacent to the horizon. In common practice, the weather observer is forced to use targets with these limitations, to varying degrees, but is unable to rigorously compensate for the non-ideal conditions.

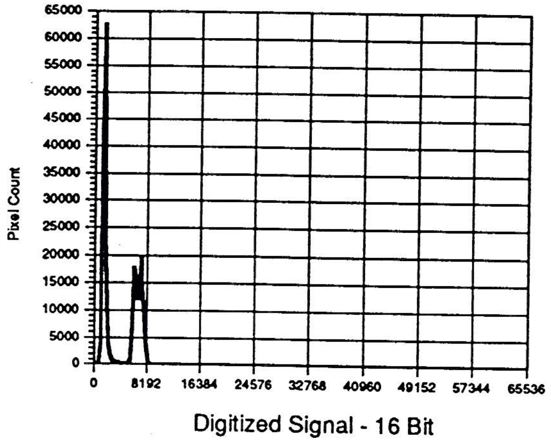

Figure 7. Historgram for Night Sky Image. The sky radiance data occupy a small portion of the radiometric range of the system. Resolution is retained through low noise and 16-bit digitization.

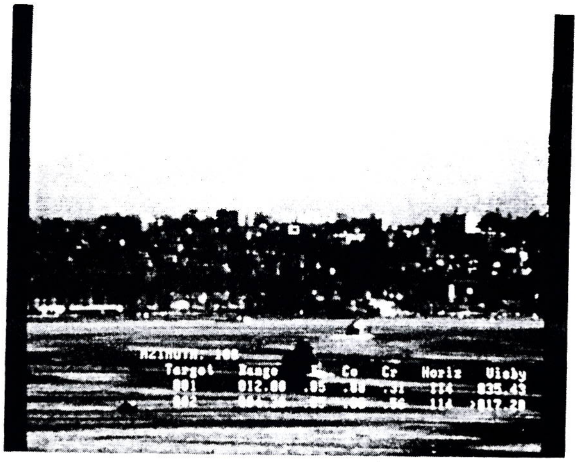

Figure 8. Sample Visibility Image. Image was acquired with the HSI, and resulting visibility computations are inserted automatically in the field.

In comparison with point scatter meters and transmissometers, the HSI has the advantage of using a long path to the target, which yields a much more representative determination. The ability to measure sector visibility, i.e. the variance around the horizon, is also important for many applications. Further discussion of the HSI system is given in Johnson, 1991a, and Shields, 1991.

3.2. DETERMINATION OF VISIBILITY AT NIGHT

Like the WSI, the HSI is being further developed for night operation. The preliminary system will use a CID sensor, just like the day system, but use on-chip integration for added sensitivity. In this mode, as photons are received and converted to electrons, the charge is collected on the chip for longer than the normal 30 milliseconds before being sensed.

The determination of visibility at night will be theoretically rigorous, i.e. based on contrast transmittance theory rather than empirical techniques, just as the determination of daytime visibility is. The system is being trained to sense lights of opportunity, such as city lights, and make the determination using either the relative measurements or the absolute measurements.

4. RELATED SYSTEM APPLICATIONS

The Whole Sky Imager and Horizon Scanning Imager, along with the WSI data base, are applicable to a broad variety of cloud-related issues. Some of the applications involve use of the instruments for operational support, whereas others involve use of the data in modeling and other applications. Some of the applications are discussed below.

4.1 TEST FACILITY SUPPORT

For operational support, a version of the WSI has been developed which makes the cloud decisions on line, i.e. at the site in near-real time. The unit acquires images every five minutes, and presents the cloud decision image within a minute after the acquisition (Shields, 1990b). The user can input a drone or satellite track of interest, and this region is identified in the image. Cloud cover for the full scene, and cloud cover along the track, are identified in the image presented to the user. During the remainder of the interval between grabs, the user may also choose to review a time lapse of archived imagery. This system is in use as a decision aid by test site support personnel.

4.2 AUTOMATED OBSERVING SYSTEMS

Automated observing systems, for automated weather monitoring, are an application area for both the WSI and the HSI systems. In response to this need, a composite system has been developed, which includes both WSI and HSI functions, as well as the on-line cloud decision capability of the real-time system discussed above. The composite system alternates between presentation of the visibility determinations and the cloud results, in the two types of format shown in Fig. 10, at a rate chosen by the user. This system has been operational for approximately 3 years, and is being upgraded to support night visibility determination.

4.3 DATA BASE APPLICATIONS

The existing WSI cloud data base provides a 3 million cloud-scene image archive, acquired at several sites over a 2-3 year period. These data are readily applicable to evaluation of models which predict CFLOS (cloud free line of sight) and CFARC (cloud free arc). (Parker, 1990,

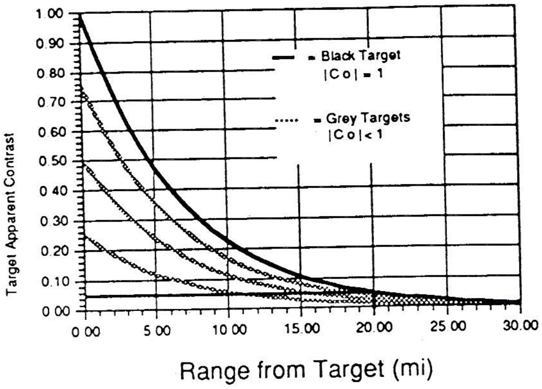

Figure 9. Apparent Contrast vs. Range. Visibility may be defined as the range at which the apparent contrast of the ideal target drops to the human visual threshold, shown as .05 in this illutsration.

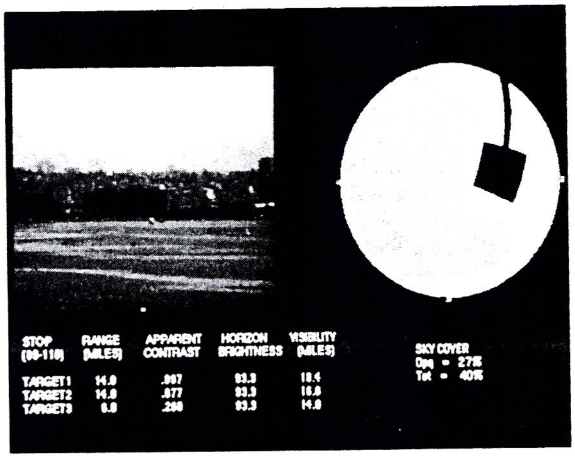

Figure 10. Composite system display. This illustrates the two types of display available on the Composite cloud/visibility system.

and Finch, 1990) The WSI data may be used in preliminary model evaluations. They are particularly useful, in that one may determine model input parameters, such as cloud cover distributions, intermediate level model products, such as CFLOS persistence, and final model outputs such as multi-site down times.

In addition, the data base has been used to generate anti-satellite test scenarios. In these studies, sample computations were made of the conditional probability that a cloud free arc of given length occur, given that the arc starts at a given zenith angle. (Koehler, 1990) There are obviously a broad variety of statistical results which may be extracted from the data base, for application to ground based systems which are impacted by cloud distributions and cloud temporal variations.

4.4 OPPORTUNITIES FOR FURTHER APPLICATION

There is currently great interest within the Global Warming community in measuring and characterizing the impacts of cloud radiative feedback mechanisms. The need for a ground based cloud imaging system to support this research effort is well recognized. The ability of the Day/night WSI, when completed, to acquire cloud images on a 24-hour basis, while simultaneously measuring the absolute radiance of the scene, could be a very appropriate contribution to this research effort.

There are a number of concepts under evaluation for extending the usefulness of the fielded systems. The use of neural networks to perform nowcasting of cloud free line of sight, and identification of cloud type, is interesting approach currently under review. Adding the ability to determine cloud height would be a strong capability. One approach under review is the use of an active system such as a ceilometer under direct control of a WSI unit. Another approach is the use of stereoscopic techniques for 3-D visualizations.

Application of the WSI systems and data base toward satellite ground truthing holds significant potential. A commonly recognized difficulty with the interpretation of satellite cloud images is the impact of sub-pixel phenomenon. The impact of this uncertainty is to a large extent driven by the resolution requirements of the given application. The ability of the WSI to identify the character of the sub-pixel cloud field, as well as the presence of thin clouds, should provide a valuable ground truth for improving cloud algorithms, and for assessing their accuracy.

4.5 THE FULL SCENE ZOOMING IMAGER

The full scene zooming imager is an approach to environmental imaging which should have considerable potential. This unit would use a 220 degree fisheye lens, to image the full upper hemisphere, as well as much of the surrounding terrain or ocean surface. A zooming imager would address the back image plane, in order to provide high resolution views of portions of the scene. This system could be trained to provide 24-hour cloud assessment and visibility determination within the same optical package, as well as visibility at sea, sea surface assessment, and bi-directional reflectances.

5. SUMMARY

The Whole Sky Imager, Horizon Scanning Imager, and related systems have developed into a set of imagers with very powerful and unique capabilities. All of these are automated systems in support of environmental research and operational requirements. The two primary systems are the WSI for cloud assessment, and the HSI for sector visibilities. From these have evolved the real time system, for on-line cloud analysis, and the composite system, with both cloud and visibility monitoring capability. Our current development effort is the extension of both the WSI and the HSI into the night-time, for eventual full 24-hour capability. In the long term, the full scene zooming imager is a system that may be expected to have all of the above capabilities, as well as monitoring of sea state and visibility at sea.

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