Marine Physical Laboratory

Analysis and Measurement of Cloud Free Line of Sight and Related Cloud Statistical Behavior

Principal Investigator(s) Janet E. Shields, Monette E. Karr, Art R. Burden, Richard W. Johnson, and Justin G. Baker

Supported by the
Office of Naval Research
Contract Number: N00014-97-D-0350-D2

Final Report

June 2003

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

University of California, San Diego
Scripps Institution of Oceanography

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. Agency Use Only (Leave Blank).

2. Report Date.
June 17, 2003

3. ReportType and Dates Covered.
Final Report

4.Title and Subtitle.
Analysis and Measurement of Cloud Free Line of Sight and Related Cloud Statistical Behavior This can must longer than usual

5. Funding Numbes.
N00014-97-D-0350-D92

Project No.
Task No.

6. Author(s).
Janet E. Shields, Monette E. Karr, Art R. Burden, Richard W. Johnson, and Justin G. Baker

7. Performing Monitoring Agency Names(s) and Address(es).

University of California, San Diego
Marine Physical Laboratory
Scripps Institution of Oceanography
291 Rosecrans Street
San Diego, CA 92106

8. Performing Organization Report Number.

9. Sponsoring/Monitoring Agency Name(s) and Address(es).

Office of Naval Research
Department of the Navy
800 North Quincy Street
Arlington, VA 22217-5660
Atten: CDR Dale Lichtey, Code 321

10. Sponsoring/Monitoring Agency Report Number.

11. Supplementary Notes.

12a. Distribution/Availability Statement.

Approved for public release; distribution is unlimited.

12b. Distribution Code.

13. Abstract (Maximum 200 words).

The Atmospheric Optics Group at the Marine Physical Lab, Scripps Institution of Oceanography, University of California San Diego, has been developing Whole Sky Imagers (WSI) for many years.. A Day/Night WSI which had 24-hour a day capability was initially developed in the early 1990's, and has been significantly upgraded in capability since that time. One of these instruments, Day/Night WSI Unit 2, was delivered to the Air Force Starfire Optical Range. This work was funded by the Air Force Phillips Lab under Contract N00014-89-D-0142 DO #18.

14. Subject Terms.
atmospheric optics, Whole Sky Imager

15. Number of Pages.
18

16. Price Code.

17. Security Classification of Report.	**18. Security Classification of This Page.**	**19. Security Classification of Abstract.**	**20. Limitation of Abstract.**
Unclassified	Unclassified	Unclassified	None

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

Analysis and Measurement of Cloud Free Line of Sight and Related Cloud Statistical Behavior

Janet E. Shields, Monette E. Karr, Art R. Burden,
Richard W. Johnson, and Justin G. Baker

1. Introduction

The Atmospheric Optics Group at the Marine Physical Lab, Scripps Institution of Oceanography, University of California San Diego, has been developing Whole Sky Imagers (WSI) for many years. (Johnson 1989, 1991). A Day/Night WSI which had 24-hour a day capability was initially developed in the early 1990's, and has been significantly upgraded in capability since that time (Shields 1993, 1998). One of these instruments, Day/Night WSI Unit 2, was delivered to the Air Force Starfire Optical Range in October 92 as documented in Technical Note AV92-051t (Shields 1992). This work was funded by the Air Force Phillips Lab under Contract N00014-89-D-0142 DO #18 (Shields 1994).

For several years, the WSI was operated at SOR without significant interaction from MPL. Then in approximately October 97, MPL was funded under Contract N00014-97-D-0350 DO #02 to perform the following primary tasks:

a) Provide a new Day/Night WSI (Unit 12)
b) Upgrade the software for Unit 2.
c) Provide analysis of Cloud Free Line of Sight (CFLOS) Statistics

In addition, the following optional tasks were funded:

a) Upgrade Unit 12 hardware and software to run under Windows.
b) Upgrade Unit 2 hardware and software to run under Windows.
c) Develop a new design for the Accessory Control Panel (control electronics).

This report documents the work that was performed under this contract. The Statement of Work is given in Section 2. All of the work has been successfully completed. A discussion of the new Day/Night WSI Unit 12 is given in Section 3. The Cloud Free Line of Sight analysis is discussed in Section 4. The upgrade to Unit 2 is discussed in Section 5. Under a subsequent contract, two additional units have been built, and additional work on the cloud algorithms has been completed. A brief overview of additional work, which has been completed under subsequent contracts, is given in Section 6.

2. Statement of Work

The Statement of Work from the proposal is as follows:

The contractor shall, unless otherwise specified herein, supply the necessary personnel, facilities, services, and materials to accomplish the following tasks within a one-year period following receipt of funding.

1. Provide an automated Day/Night Whole Sky Imager for detection of day and night sky fields. This includes software for the automated acquisition, as well as a cloud decision algorithm for the daytime opaque clouds. Limited networking capability will also be included.

2. Upgrade the software on the current SOR WSI for compatibility with the current generation software delivered with the new WSI, except as limited by differences in the hardware of the two WSI's.

3. Analyze and process existing cloud decision images acquired by an earlier generation Day-only WSI to provide statistics related to Cloud Free Line of Sight (CFLOS) and the temporal behavior of the cloud free line of sight. Desired statistics and the relative priority of completion will be set in joint cooperation with the sponsor, and analysis will proceed to the extent possible within the budget limitations.

The above was slightly modified by the receipt of funding for one of the options, in approximately September 98. The funded option is extracted from the Options Statement of Work in the proposal:

4. Upgrade the computer and camera hardware to enable use of a Pentium and Windows-based operating systems. Begin development of a software conversion to enable use of the software under windows, with the intent of converting the WSI acquisition program for use under windows if possible within the funding limitations.

The sponsors included funding for upgrading both Unit 12 and Unit 2 to the Windows configuration. In addition, as part of this work, they included funds for designing a new Accessory Control Panel.

All of this work was completed successfully. Item 1 was completed and Unit 12 was delivered in January 99, as documented in Technical Memorandum AV99-030t (Shields 1999d). This delivery included the hardware and software upgrades in Item 4. Item 3, the CFLOS analysis, was completed and delivered in a series of deliveries on March 98, August 98, and January 90.

In approximately June 99, SOR funded MPL for follow-on work, under Contract N-00014-97-D-0350 DO #06. This work included providing two more WSI units, Units 13 and 14, as well as additional options, including further upgrades to Unit 12. At the sponsor's request, the work under Task 2 of the first contract, i.e. the work to upgrade Unit 2, was postponed because they felt that this new work on Units 12, 13, and 14 was higher priority. The work on Unit 2 was completed in 2001.

To the best of our knowledge, all work funded under the original contract discussed in this report has been completed, and the sponsors are very happy with the work.

3. The New Day/Night WSI, Unit 12

The Day/Night WSI is a fully automated digital camera system designed to acquire images of the sky under all conditions from daylight through starlight. The new unit developed under this contract is shown in Figure 1.

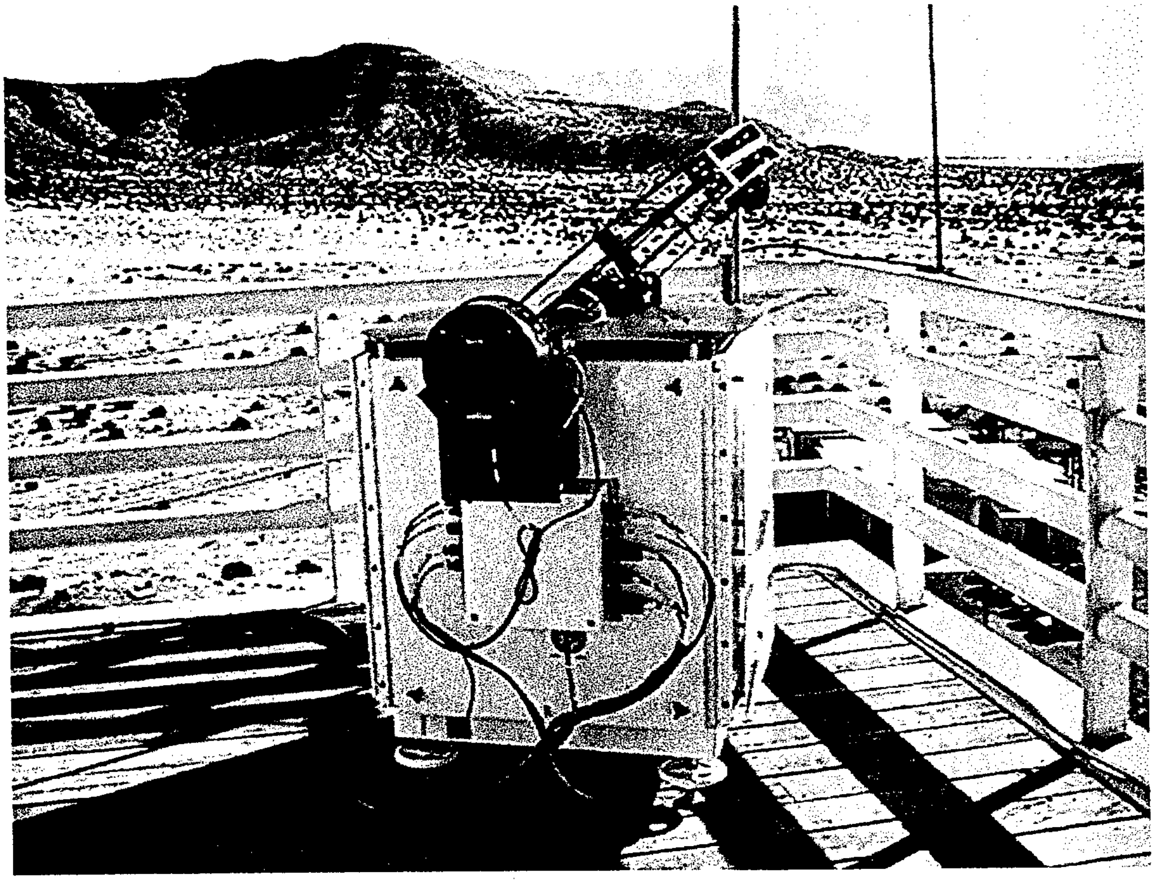

Figure 1. Day/Night WSI Unit 12 delivered to SOR

During the time since Unit 2 had been built, many upgrades to the Whole Sky Imager design have been completed. The new instruments (Units 3 – 11) are more robust, with a stronger occultor and safer environmental housing. Numerous self-checks have been added to the system; for example, the system monitors the CCD (Charge Couple Device) temperature, the camera housing temperature, and the environmental housing temperature, and it can turn off the camera automatically if system temperatures become dangerously high. The software has also developed considerably since Unit 2 was built. New features included networking of the system, and daytime cloud algorithm for opaque clouds. The cloud algorithm is, on some instruments, integrated into the archival software to provide the cloud algorithm results (called the cloud decision image) as the data are acquired.

Unit 12 included all of these upgrades, as well as several newer upgrades, as documented in Technical Memo AV99-002t (Shields 1999a). The upgrades funded under this contract are documented in Sections 3.1 and 3.2.

3.1 Hardware Upgrades

While all of the Day/Night WSI units have used a Photometrics 16 bit digital camera, Unit 12 was the first system with a Series 300 camera, rather than a series 200 camera. The primary difference is that the Series 300 camera is compatible with a Pentium-style CPU (Central Processing Unit) card. Like the Series 200 cameras, the Unit 12 camera is a very low noise high dynamic range camera. Unit 12 used a 512 x 512 Scientific Grade 1 Thomson CCD, with a tapered fiber optic bundle bonded to the CCD. This camera also used a newer version of the CCD, which has MPP (Multi Pin Phase) mode for lower dark current noise, without the corresponding loss in dynamic range that MPP mode used to entail.

Like previous units, Unit 12 includes a 2-wheel filter changer, a Nikon 8mm f/2.8 fisheye lens, and a tapered fiber optic bundle. The lenses, filters, and camera input end are housed in the camera housing, which provides a dry nitrogen environment to protect the optics. The camera housing is slightly different from Unit 2, in that the back end of the camera protrudes from the housing, so that if there are any leaks in the coolant tubing, the leak will be external to the camera housing. This unit also includes a pressure sensor, which monitors the pressure of the dry nitrogen used in the camera housing, as well as the temperature outputs mentioned earlier.

The environmental housing is an aluminum housing with a temperature-stabilized interior. By keeping the interior of the housing cool and dry, this should provide superior lifetime to the camera electronics unit. Unit 12 uses a McLean recirculating cooler rather than the Teca cooler used in some of the units, because the Teca proved to be unreliable. Unit 12 is also the first unit with the new junction box. This junction box provides a mechanically cleaner input of power and input/output of signals. Also, the internal wiring in the environmental housing has been simplified, and terminal strips are now inside a protected case.

We found the occultors used on Units 1 and 2 to be difficult to maintain, due to the high forces inherent in a cantilevered system. Starting with Unit 3, we converted to an arc which travels East to West and supports a trolley which travels from North to South. Unit 12 includes the recent upgrades to the arc drive included on several recent instruments, including the brake and the slip clutch. Unit 12 is the first instrument with an upgraded trolley drive. The trolley drive now includes a slip clutch, stronger drive chains, and a single pull system with different gears that are less likely to slip and require adjustment. The trolley upgrade is discussed in more detail in Memo AV98-076t (Wertz 1998).

The controller housing was upgraded after Unit 2 to provide an environment for the computer that is relatively protected from dust. The Accessory Control Panels (ACPs) have been upgraded to include feedback of the state of the environmental housing, including chip temperature, camera housing temperature, environmental housing temperature, coolant flow rate, camera housing nitrogen pressure, and relative humidity of the environmental enclosure. The computer has been upgraded to a Pentium CPU. The archival mechanism has been upgraded from a Exabyte tape to a JAZ Drive. Unit 12 is the first unit with a Pentium CPU. Although a Jaz drive was used on the original delivery, at the sponsor's request, this was later changed due to reliability issues. As discussed in Section 6, an additional processing computer was added to the system under a later contract. This additional computer enabled near-real processing of the data with faster acquisition intervals.

In the fabrication of the instrument, vendor-supplied items were used where possible. For example, the CCD camera, which is one of the most critical components, was built with the bonded fiber optic taper especially for MPL by Photometrics. MPL's machine shop fabricates most of the mechanical components for subassemblies such as the camera housing and solar/lunar occultor, and these subassemblies were built by MPL. The electronics control packages such as the Accessory Control Panel were built by MPL, using vendor-supplied components where possible.

An important part of the assembly is the instrument testing which goes on throughout the development. For example, the testing of the camera components includes tests for precision and uniformity, linearity, and radiometric sensitivity. For Unit 12, absolute radiance distribution was not originally a required product, however the calibrations are important in validating system performance. Calibrations were performed in November and December 98 prior to delivery. Tests of software, electrical and mechanical assemblies, and the completed unit were also part of the effort.

Documentation was provided in the form of memoranda. These are listed in the references, Section 9, and are available on request.

3.2 Software Upgrades

Program RunWSI was rewritten for Unit 12 to run under Windows 95. This involved considerable changes to the user interface, the camera control, and the image processing subroutines.

One of the major changes to RunWSI was made to accommodate the new Photometrics camera and its library of routines. Photometrics updated their software library so that it is compatible with all of their cameras and several different operating systems including Windows 95. Although the interface for camera setup and image acquisition is quite different from previous versions, it was a straight-forward process to implement the changes. The image–handling software was changed significantly, because the Windows version of the image processing library used in the earlier code did not support 16-bit images. The solar/lunar occultor software was completely upgraded.

A new internal GPS (Global Positioning System) clock was added to the system as the internal time source. This internal GPS card was chosen rather than a hand-held GPS used in several recent units because the GPS card does not turn itself off when there is low antenna signal. The new program is documented in Memo AV99-001t and AV99-009t (Karr 1999a and b).

A sophisticated instrument interface was added to the system software. This interface was designed to work with the "E-PAODMS" system designed by another contractor. The interface allows another system to specify regions of interest (ROI), as well as a number of other parameters related to desired output. The WSI reads these files, and then can send the desired data to another system. This data can include WSI status, cloud cover statistics, raw or processed images, and cloud information within the desired ROI. These ROI positions can move, as the position of the target of interest moves. My understanding is that these capabilities were never fully utilized, due to problems with the E-PAODMS, however this is a very powerful capability and could easily be adapted for a number of purposes. The interface is documented in Memo AV98-043t (Karr 1998c). Additional technical memoranda documenting the software and its use were provided to the sponsor, and are listed in the references. They are available on request.

Considerable additional development of the software has occurred under subsequent contracts, and is discussed briefly in Section 6.

4. Cloud Free Line of Sight Study

As part of this contract, we were funded to do a statistical study of Cloud Free Line of Sight (CFLOS), using a data base of WSI data taken in the late 1980's with the Day WSI (EO System 5) as documented in Johnson et al 1989. This data base consisted of cloud images acquired at full resolution every 10 minutes, and partial resolution every 1 minute. The full resolution data have 1/3 of a degree pixel resolution. The partial resolution images include rows and columns which are at 1/3 degree resolution, but which are separated by roughly 5 degrees between rows and columns. The data had already been processed through the cloud decision algorithm to yield assessments of opaque cloud, thin cloud, or no cloud in each pixel.

The purpose of the study was to determine CFLOS for existing satellites, as well as related statistics such as persistence, and various conditional probabilities, as will be discussed below. The studies are detailed in several technical memos that are included in the appendix. In this discussion, we will merely summarize the results and give a few examples.

Data were processed for five sites:
WSC: White Sands C-Station, New Mexico (desert)
KAA: Kirtland AFB, New Mexico (desert)
COL: Columbia, Missouri (city in plains area)
MAG: Malmstrom AFB, Great Falls, Montana (northern plains)

BAR: Malabar, Florida (coastal)

The most simple statistic is the probability of having a cloud free line of sight in a given direction. We were asked to extract these statistics for two directions, namely the direction to the GOES-8 and the GOES-9 satellites. (The zenith and aziumuth angles vary by site for these specific satellites. Table 4-1 shows the probability of CFLOS for all cases, for these two directions. Note that the probability is higher for desert sites, as expected.

Table 4-1
PCFLOS for 2 satellite directions, all cases

	WSC	KAA	COL	MAG	BAR
GOES-8	0.62	0.64	0.46	0.34	0.41
GOES-9	0.63	0.66	0.45	0.38	0.45
Number of cases	24000	23798	23053	13446	10449

The number of cases is also show in Table 4-1. Due to the very large number of cases in this database, further analysis of variation as a function of cloud fraction, season, and other variables could be studied.

The probability of cloud free line of sight is strongly driven by the fractional cloud cover. Table 4-2 shows the impact of cloud fraction for the GOES-8 direction.

Table 4-2
PCFLOS as a function of Cloud Fraction

Cld Fraction	WSC	KAA	COL	MAG	BAR
0.0	0.99	1.00	0.98	0.97	0.98
0.1	0.95	0.95	0.94	0.86	0.78
0.2	0.85	0.86	0.86	0.72	0.73
0.3	0.71	0.73	0.77	0.64	0.64
0.4	0.63	0.61	0.63	0.61	0.51
0.5	0.54	0.50	0.54	0.44	0.41
0.6	0.42	0.41	0.40	0.36	0.31
0.7	0.31	0.34	0.32	0.36	0.19
0.8	0.19	0.19	0.19	0.24	0.11
0.9	0.08	0.09	0.06	0.13	0.06
1.0	0.00	0.01	0.00	0.99	0.00
Cum	0.62	0.64	0.46	0.34	0.41

The CFLOS is obviously expected to depend strongly on cloud fraction. The precise character of the dependence is in turn a function of zenith angle. A fairly early model of the expected variation of PCFLOS as a function of cloud fraction for the zenith direction is shown in Figure 4-1. This plot was provided courtesy of TASC. The straight-line relationship could be expected with uniformly small clouds of zero physical thickness.

Allowing for the physical thickness of clouds, and realizing that a lower look-angles we often see the sides of clouds, accounts for a somewhat increased PCFLOS in the vertical direction for intermediate cloud fraction amounts. In this early plot, the TASC analysts had noted an interesting departure from this model with a limited set of WSI data.

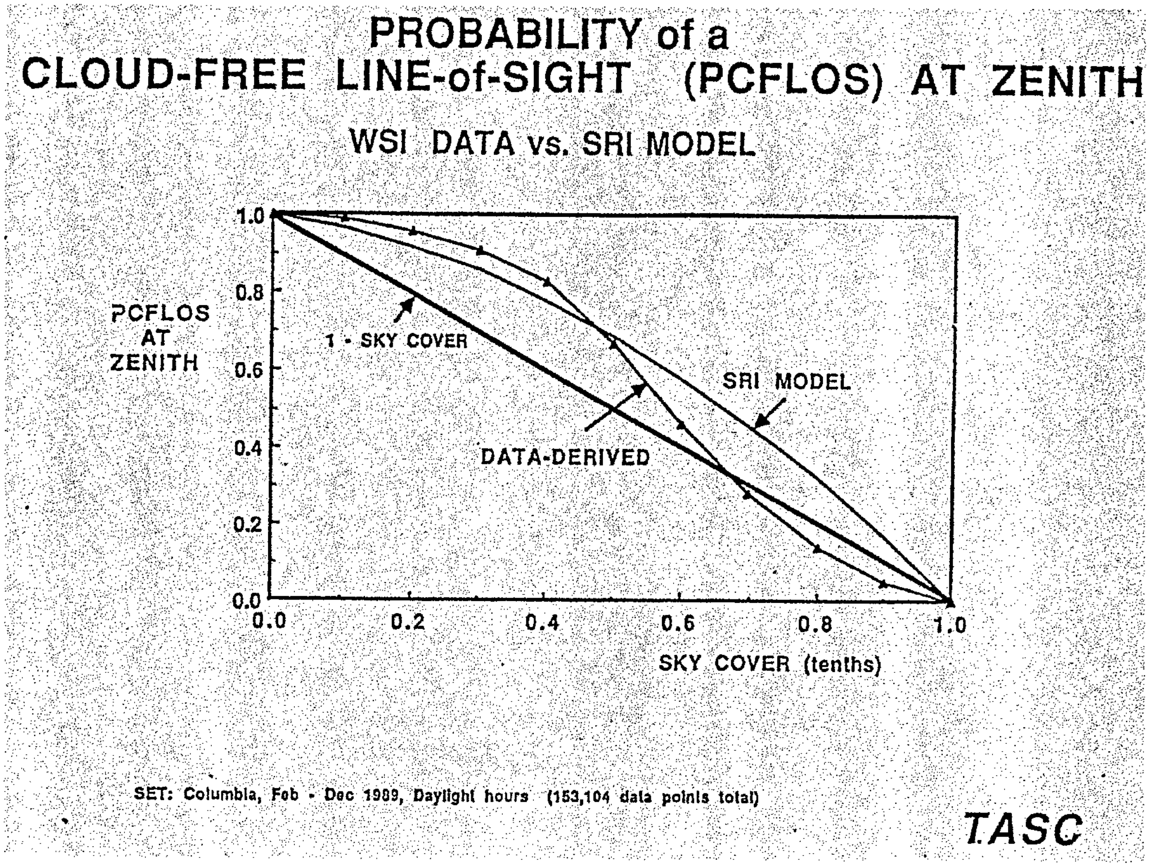

Fig. 4-1 TASC Model Data and WSI data from COL site, PCFLOS at zenith vs sky cover

As shown in Figure 4-2, the larger data set supports this more complex relationship first noted in the data in Fig. 4-1. We note that when the cloud fraction exceeds values of approximately 0.7, the PCFLOS at the zenith is lower than might be anticipated. We believe this is because cloud fractions of 0.7 are often associated with a single cloud sheet, which covers 70% of the sky, rather than many small clouds covering 70% of the sky. When a single large cloud region covers more than half of the sky, then of course the zenith is nearly always covered. For this reason, the decrease in zenith PCFLOS, and corresponding increase in PCFLOS at lower look angles, seems reasonable.

Another interesting statistic is the probability that at least one site will be clear in the desired direction, if there are several sites available. Table 4-3 shows the probability that at least X sites are clear, given the availability of 4 sites. With 4 sites available, it is rare that there are no clear sites, and rare that all four sites are clear. However, the probability that at least 1 site is clear is quite high, over 90% for these sites. Table 4-4 shows similar results for cloudy lines of site.

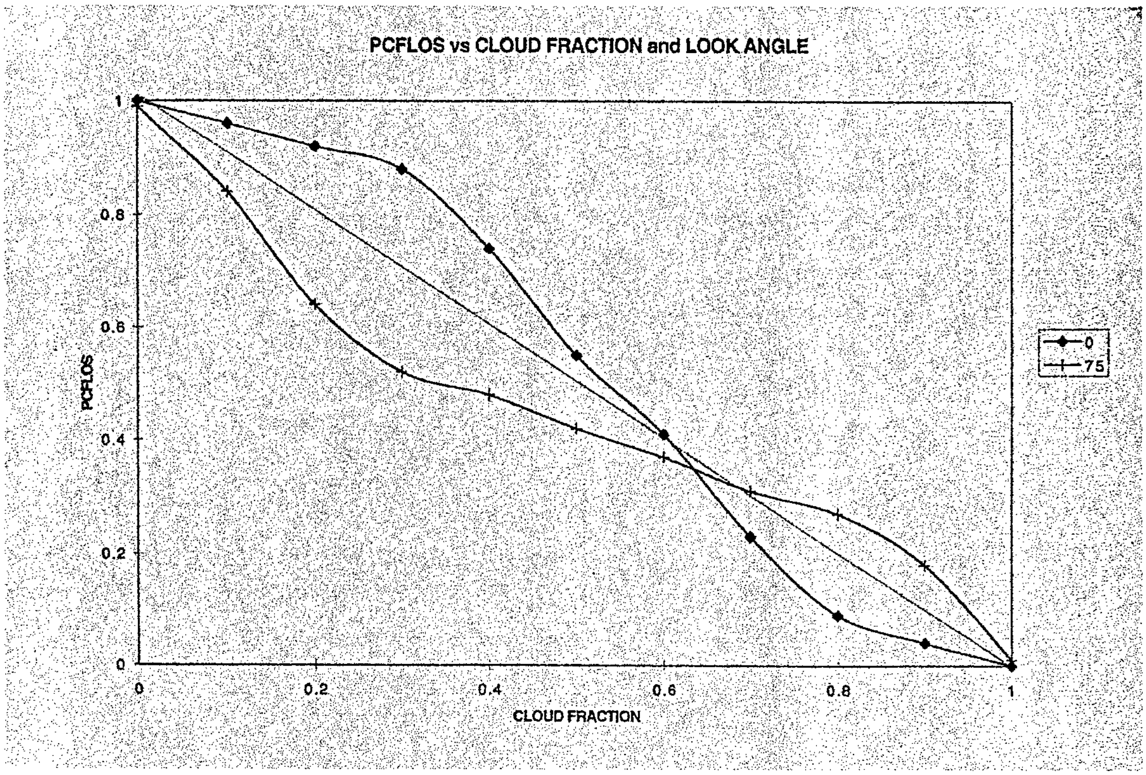

Fig. 4-2. PCFLOS at zenith and at zenith angle 75 degrees, full processed data set

Table 4-3
Probability that at least X sites are clear in a given direction
When there are 4 sites available

	No Sites Clear	At least 1 Site Clear	At least 2 Sites Clear	At least 3 Sites Clear	At least 4 Sites Clear	Number Of Observations
Goes-8	0.08	0.92	0.73	0.40	0.10	7909
Goes-9	0.09	0.91	0.74	0.42	0.11	7698

Table 4-4
Probability that at least X sites are cloudy in a given direction
When there are 4 sites available

	No Sites Cloudy	At least 1 Site Cloudy	At least 2 Sites Cloudy	At least 3 Sites Cloudy	At least 4 Sites Cloudy	Number Of Observations
Goes-8	0.10	0.90	0.69	0.27	0.08	7909
Goes-9	0.11	0.89	0.58	0.26	0.09	7698

The probability that a given number of sites have a clear line of sight depends, of course, on the number of sites available. For example, if we take those cases in which there were three sites available, we get the results shown in Table 4-5. Comparing these with the results in Table 4-3, we see that the probability of having at least 1 site clear is nearly as high with only 3 sites, but the probability of having 2 sites clear, or 3 sites clear, is much less.

Table 4-5
Probability that at least X sites are clear in a given direction
When there are 3 sites available

	No Sites Clear	At least 1 Site Clear	At least 2 Sites Clear	At least 3 Sites Clear	Number Of Observations
Goes-8	0.12	0.88	0.59	0.16	8840
Goes-9	0.12	0.88	0.60	0.17	8584

The sponsors were also interested in knowing whether it is useful to monitor one direction, in order to predict the results in another direction. In Table 4-6, we show the impact of knowing that the sky is clear in the direction of Polaris.

Table 4-6
PCFLOS as a function of cloud fraction at WSC site for GOES-8 direction:
Unconditional, and Conditional given Polaris is clear

Cloud Fraction	PCFLOS	PCFLOS Given that Polaris is Clear
0.0	0.99	0.99
0.1	0.95	0.95
0.2	0.85	0.81
0.3	0.71	0.66
0.4	0.63	0.54
0.5	0.54	0.39
0.6	0.42	0.27
0.7	0.31	0.14
0.8	0.19	0.11
0.9	0.08	0.02
1.0	0.00	0.00
Cum	0.62	0.90

First, look at the last entry, the cumulative results. The knowledge that Polaris is clear has a strong impact on the cumulative PCFLOS results; that is, considering all cases of cloud fraction, if Polaris is clear, the PCFLOS goes up from 62% to 90%. However, if the cloud fraction is known, the knowledge of whether Polaris is clear is much less important. For example, if the cloud fraction is 0.0 or 0.1, the PCFLOS for the GOES-8 direction is actually lowered if Polaris is clear. This occurs because Polaris is quite distant from GOES-8 in the sky at WSC. Polaris is at an azimuth angle of 1° degree, and GOES-8 is at 131°. Were Polaris and GOES-8 directions close together, we would Polaris to be a much better predictor of the PCFLOS, even if the cloud fraction is known.

Temporal Persistence of the cloud-free or cloudy condition in a given direction is another characterization of the cloud field that is important for certain applications. The persistence is more precisely defined in the memos in the appendix. If, at time T_0, a given direction is clear, persistence give the probability that it remains clear during the interval from T_0 to time T.

Figure 4-3 shows typical persistence results. In the upper left of Fig. 4-3 are persistence values for WSC station, as a function of season. At this station, season was not a strong driver; in contrast, the data on the upper right for COL shows a strong seasonal dependency. The lower plots show the results for two different directions; the two directions yielded similar results for both stations.

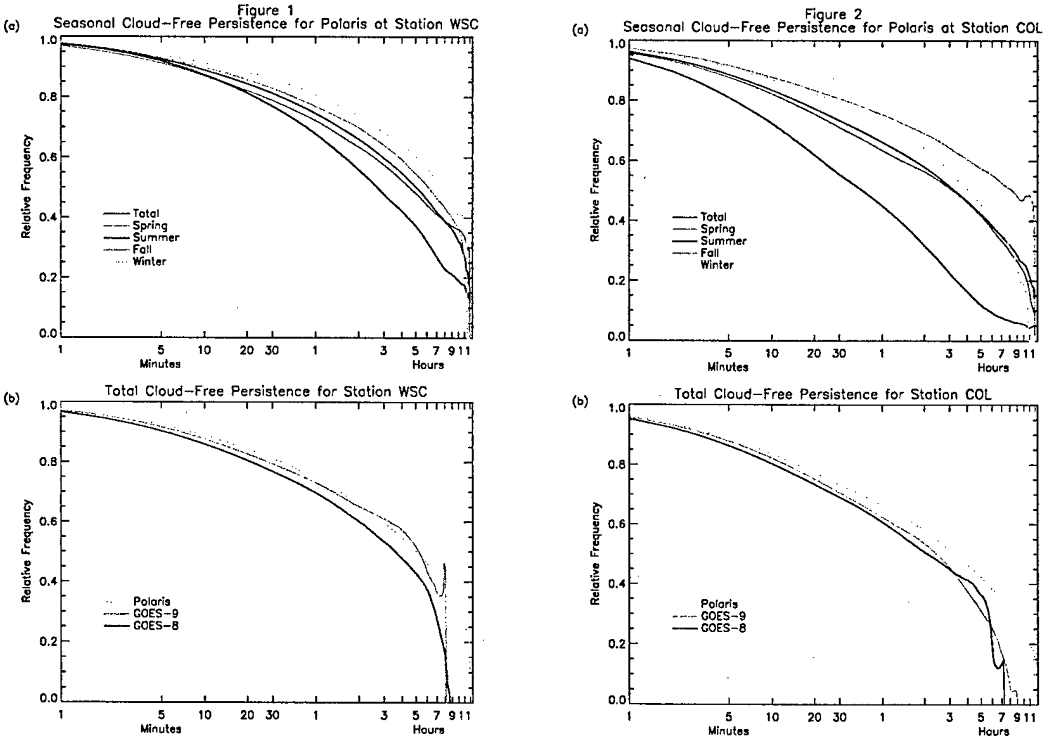

Fig. 4-3. Persistence of Cloud-free conditions as a function of season and line of sight at two stations. Figures are extracted from Memo AV99-004t.

Results can vary significantly by site. Figure 4-4 shows results for the 5 sites, for both cloud-free persistence and cloudy persistence. As expected, the cloud-free persistence is higher for the two desert sites than the other sites. Interestingly, BAR, the Florida site, has the lowest persistence for both cloud and cloud-free conditions, reflecting the prevalence of small fast-moving clouds at this sight.

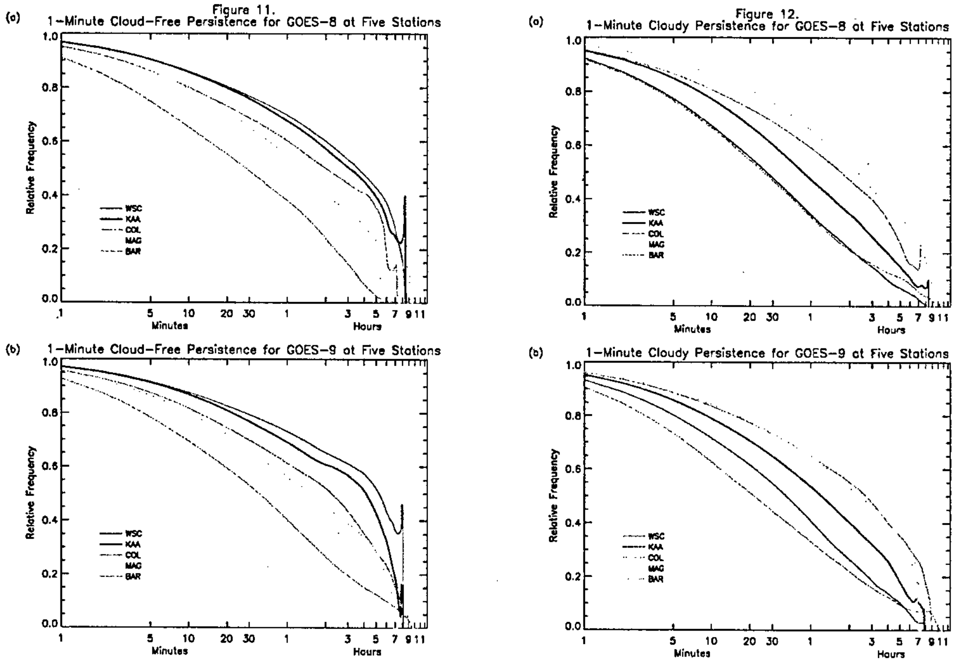

Fig. 4-4. Persistence of Cloud-free line of sight and Cloudy line of sight for all five stations. Figures are extracted from Memo AV99-004t.

A convenient way to illustrate the persistence statistics is to evaluate how long it takes for the probability of persistence to drop below 50%. These values are given for both cloud-free and cloudy line of sight in Table 4-7.

Table 4-7.
Time Required for Yearly Persistence
Probabilities for Polaris to Drop Below 0.5
(in minutes)

Station	Cloud-Free	Cloudy
WSC	305	41
COL	186	156
KAA	246	65
MAG	90	176
BAR	47	22

A number of other statistics related to persistence are given in the appendix. These include multiple-station persistence, such as the probabilities that more than one station will remain cloud-free for a given interval, as well as similar multiple-direction statistics.

5. Upgrades to Unit 2

The Day/Night WSI Unit 2 was one of the two original Day/Night WSI units first developed and built in the early 90's. As discussed in Section 3, many upgrades to the

ONR/MPL REPORT DISTRIBUTION

Office of Naval Research (3)
Department of the Navy
Ballston Tower One
800 North Quincy Street
Arlington, VA 22217-5660
Atten: CDR Dale Lichtey, Code 321

Regional Director (1)
ONR Detachment
San Diego Regional Office
4520 Executive Drive, Suite 300
San Diego, CA 92121-3019

Commanding Officer (1)
Naval Research Laboratory
4555 Overlook Avenue, S.W.
Attn: Code 2627
Washington, D.C. 20375-5320

Defense Technical Information Center (4)
8725 John J. Kingman Road
Suite 0944
Ft. Belvoir, VA 22060-6218