

ARMY RESEARCH LABORATORY



Validation of the Atmospheric Transmission Large-Area Analysis System (ATLAS)

by Max P. Bleiweiss



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13. ABSTRACT (Maximum 200 words) The Atmospheric Transmission Large-Area Analysis System (ATLAS) is a unique tool that has been under development at the U.S. Army Research Laboratory since the mid-1980's. ATLAS is a nonintrusive, passive technique capable of producing two-dimensional transmittance maps of a smoke cloud in a plane perpendicular to the main-optical-axis line of sight (LOS). (Off-axis LOSs are not perpendicular but are in a fan with an angular intersect determined by the overall field of view of the imager.) (The accuracy and precision of the transmission values depends on the test conditions during which the measurements are made but can be defined through the error analyses discussed in this report. The spatial resolution of the resulting transmission maps is also test specific, but, typically, is of the order of a few tens of centimeters. The temporal resolution is determined by the video rates of the imaging system, which, after preliminary low-pass filtering, yields maps at 10 Hz.) ATLAS is at the stage of development that it is used on a regular basis to support smoke/obscurant field tests. For this reason, a validation process was defined and implemented in 1989. This report documents the completion of that effort as a major milestone for the laboratory during FY92. In addition, the capabilities and limitations of the ATLAS technique are discussed in detail.			
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1. Introduction

The Atmospheric Transmission Large-Area Analysis System (ATLAS) is a nonintrusive, passive technique in which two-dimensional transmittance maps of a smoke cloud in a plane perpendicular to the line of sight (LOS) are produced. (Off-axis LOSs are not perpendicular but are in a fan with the apex at the imager; however, because of the geometry, the approximation is not too far wrong.) Generally, ATLAS is a technique that uses an imager as a receiver and the natural background scene radiance or targets of opportunity* as the source to form a transmissometer system. Figure 1 is a schematic of the process. Typically, the background scene radiance, prior to the presence of smoke, is recorded and saved for comparison to the scene when smoke is present. Through a variety of algorithms, the cloud radiance under optically thick conditions is determined and, along with the processing of the two scenes (clear air and with aerosol present), yields a transmittance map. The advantage in using ATLAS over conventional techniques is its passive, nonintrusive capability and ability to measure the whole scene as opposed to a single LOS. A traditional transmissometer only samples the equivalence of a single pixel in a scene, whereas, ATLAS samples $\approx 200 \times 200$ pixels (the image array size). For typical test scenarios, this yields spatial resolution for the transmittance field of the order of a few tens of centimeters; if desired, it could be as small as a few centimeters. The temporal resolution is determined by the video rates of the imaging systems being used (30 frames/s; low-pass filtered to yield data at 10 Hz). A disadvantage of the current instrumentation setup is that the precision of the transmittance measurements determined by ATLAS is a few percent, because of low dynamic range. More conventional systems can measure transmittance levels of fractions of a percent. When there is insufficient natural scene radiance or targets of opportunity for determining transmittance, it is possible to place sources in the field of view and use the imager as the receiver and retain a certain degree of versatility. This latter mode can also be used for measurements in other portions of the spectrum

*A "target of opportunity," as used in this report, is defined as a localized region of the image that is considerably hotter than the surrounding background. The target of opportunity may be caused by a natural or cultural feature that appears hotter.

(visible, near-infrared (IR)) where scattering may dominate and the ATLAS algorithm is no longer valid.

ATLAS provides two-dimensional transmittance through the cloud so the full vertical and horizontal extent of the cloud, relative to its screening characteristics, can be determined. ATLAS can also assess impossible LOSs (elevated platform (slant path) or other horizontal LOSs not amenable to instrumentation) that would otherwise be inaccessible to measurement. Another ATLAS utility characterizes diffusion and transport processes to a degree not previously attained.* [1] In addition, the creation of a library of real smoke clouds for use in simulations/simulators is just being realized. [2] It is only with ATLAS that such measurements and tools are available.†

Because of the importance of the products of ATLAS processing, and as with any measurement technique, it is necessary to document the capabilities and limitations of the process. This effort is described in this report as a validation effort. This report describes the validation process used on ATLAS and the progress and results of the validation. It is to be understood that the validation process is an evolving and continual process as is the ATLAS technique itself. The progress with the ATLAS technique will develop as it is used and as new situations requiring its use become known.

*Cloud 8904 was been supplied in part to, and is being used by, the developers of the Battlefield Environment Weather Simulation System. [3]

†This statement is valid because there are no other systems capable of freezing the cloud; for example, LIDAR systems require pulse rates of the order of tens of kHz to sample the cloud rapidly enough to ensure no significant cloud movement during the measurement period; such systems do not exist.

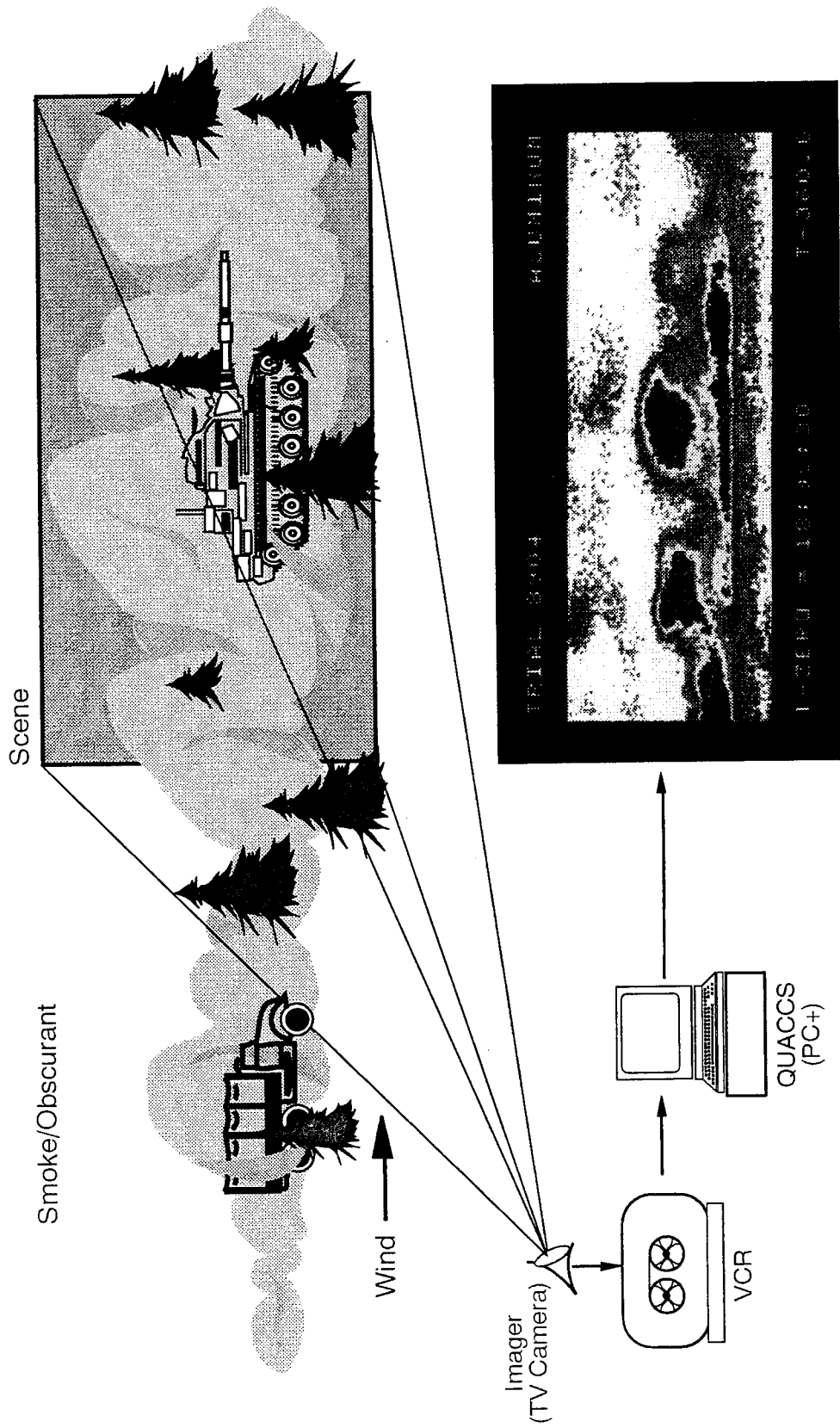


Figure 1. The ATLAS process shown schematically. The scene, containing a variety of natural and manmade objects, is imaged before and during the presence of smoke. The images, acquired with a thermal imager, are recorded to video tape for later data reduction that is accomplished with a pc-based image processing system.

2. Validation Process

The starting place for the validation process is analyses of the physics used in the ATLAS technique. For the physics, it was required that a detailed assessment be made of the radiative transfer process. As part of the assessment, it was necessary to determine the assumptions that were being made with the ATLAS algorithm and to define the limitations imposed on the process by those assumptions. Error analyses were performed and implemented because an important part of a validation procedure is knowing the errors of the measurement. The mitigation efforts that might be imposed to alleviate the limitations of ATLAS and ensure that the remaining assumptions are being addressed are discussed. The bulk of the analytical part of the validation process was carried out by Vonder Haar and associates at Colorado State University (CSU) and Metsat, Inc. These findings were presented in a series of reports and a symposium proceeding. [4,5,6,7] Empirical assessment was accomplished within the work unit and continues to advance with every new test; the efforts were presented at several symposia. [6,8,9]

2.1 Physics

The equation of radiative transfer (band-averaged) is given in equation (1):

$$N_R = N_c e^{-\tau} + (1-\omega)(1-e^{-\tau})B + \omega(1-e^{-\tau})N_e \quad (1)$$

where

- N_c = the clear air radiance of background scene element
- B = the Planck blackbody function of the cloud (cloud radiance)
- N_e = the environmental radiation that scatters off the cloud
- τ = the optical depth
- ω = the single scattering albedo

Because it is not practical to measure or know all the terms for ATLAS processing, assumptions concerning the relative importance of the various quantities must be made.

2.2 Assumptions

Because the measurements made during ATLAS data acquisition are in the far-IR portion of the electromagnetic spectrum, the following assumptions can be made to make the analyses more tractable:

1. A single scattering of background radiance is through the cloud; otherwise, the extinction involves multiple scattering that cannot be accounted for in the algorithm used for ATLAS processing.
2. The scattering portion of the extinction coefficient is small.
3. The background radiance is temporally constant.
4. The background radiance is sufficiently different from the cloud radiance.
5. The grey level is proportional to radiance.
6. Aerosol is at ambient temperature and the cloud is the same temperature everywhere, which implies that the cloud radiance is the same everywhere*.
7. The presence of smoke does not significantly affect the characteristics of the ambient clear atmosphere.

*Although the temperature in the atmosphere varies with height, no difference in cloud radiance with position in the cloud was detected, which could be ascribed to variable air temperature (this has not been formally documented).

The application of these assumptions allows equation (1) to be abbreviated to

$$N_R = N_C e^{-\tau} + (1 - e^{-\tau})B \quad (2)$$

or, rearranging,

$$T = \frac{N_R - B}{N_C - B} \quad (3)$$

where

$$T = e^{-\tau}, \quad (4)$$

which is what ATLAS measures, and B becomes the limiting cloud radiance under optically thick ($\tau \rightarrow \infty$) conditions.

2.3 Limitations

Ensuring that the assumptions are valid during the measurement process requires that limitations be placed on the use of the ATLAS technique. The limitations of the technique appear when the assumptions are no longer valid, and in fact, new assumptions are discovered as new limitations appear. ATLAS is not a cure-all and does not work in all instances; therefore, as it is used, new limitations will surface. The current inventory of major limitations consists of the following:

1. Unless the background scene radiance is much different from the cloud grey level, a measurement at that pixel location cannot be made, which can place holes in the data and make large regions of the image not available for analyses. The *a priori* determination of acceptable versus unacceptable test conditions is yet to be accomplished with certainty and laid down as a set of rules for test conduct.
2. Along with the first limitation, not only does the scene radiance need to be different from the cloud grey level, but it needs to be sufficiently different to allow meaningful measurements; the quantification of the required difference, *a priori*, remains to be accomplished. However, the

application of the error analyses algorithm allows the customer to select this parameter based on the error in the measurements, which is acceptable.

3. To use the ATLAS algorithm, the cloud grey level must be known. Usually, a target of opportunity coupled with a nearby background scene element can be used to arrive at that number. If there are no such hot spots, the analyses cannot proceed. Another way to get at the cloud grey level is to have a transmissometer along an LOS in the field of view, which is not always possible. Until a reliable, nonintrusive technique for determining cloud grey level is developed, determining cloud grey level will be a major limitation on processing of ATLAS data. This limitation is the primary reason real-time ATLAS is not successful; the tools (hardware and software) are there to process the images, etc. but not the *a priori* determination of cloud grey level.
4. Environmental (ambient) radiation scatters off the cloud into the field of view (path radiance) contributing a factor that cannot be accounted for with the current tools used in ATLAS analyses.
5. Background scene radiance is not constant with time.

In spite of these limitations and the lack of *a priori* information that allows a predetermination of the success or failure of test support, most of the time viable products are provided to the customer, and the concomitant learning process improves future products.

2.4 Error Analyses

The derivation of the error analyses is based on standard error analyses procedures delineated by Beers [10] and applied in the CSU/Metsat reports. The errors in output transmittance are due to error propagation from the ATLAS algorithm input variables. Input to the error analyses equations are estimates of the error absolute standard deviation. For the purposes of discussion, the ATLAS algorithm is restated with different symbols used for the variables:

$$T = \frac{GLC - GLS}{GLB - GLS} = \frac{N_R - B}{N_C - B} \quad (5)$$

where

GLC = the grey level of the current pixel location at the current time
 GLS = the grey level of the smoke cloud under optically thick conditions
 GLB = the grey level of the current pixel at some time before smoke in clear air.

The analyses only apply to this algorithm. If the ATLAS algorithm is modified, the error analyses must be updated. If one or more of the basic assumptions is seriously violated, the error analyses are meaningless (because different relationships among the variables will exist).

A discussion of the error estimates for each of the variables in equation (4) follows. The error estimates of GLC are made from the determination of radiometer accuracy (nominally 0.5 K -- for the gain setting used in this example) and effects of multiple scattering. For an instrument dynamic range of $\Delta T = 10$ K, the estimate in grey level counts (for 8 bits dynamic range = 256 grey levels) is $\approx \pm 13$ counts. The scattering effects are $\approx \pm 4$ counts. [6] Therefore, an example of the absolute standard deviation of GLC is given by

$$s_{GLC} = \sqrt{4^2 + 13^2} = \pm 13.6 \text{ counts} \quad (6)$$

The error estimate for GLB is primarily determined from radiometer accuracy. A way to reduce this value is to average several N clear air frames:

$$N \text{ images} \rightarrow \frac{1}{\sqrt{N}}(\pm 13) \quad (7)$$

(Significant averaging of frames to reduce s_{GLC} is not possible because the scene is dynamic during the presence of smoke and the averaging would wash out the dynamics of interest; however, there is some low-pass filtering required in the data reduction process to ensure that the results are presented without aliasing.)

The error estimate of GLS is derived from the procedures used to arrive at GLS. The best fit correlation can be used to produce a minimum absolute standard deviation; or an estimate of the scatter in the value can be made analytically or by eye. There may also be biases present in the determination of GLS because of the technique or some unaccounted for problem (such as stray path radiance). As better ways evolve to determine GLS, the error estimate should become more objective and, hopefully, smaller.

The calculation of the error needs to consider three separate cases because different procedures apply for each. The first is the case in which $GLC \neq GLS$. Equation (4) is rewritten as

$$x = GLC - GLS \quad (8)$$

$$y = GLB - GLS \quad (9)$$

$$T = \frac{x}{y}. \quad (10)$$

The absolute standard deviations of the ATLAS variables are used by

$$s_x = \sqrt{s_{GLC}^2 + s_{GLS}^2} \quad (11)$$

$$s_y = \sqrt{s_{GLB}^2 + s_{GLS}^2}. \quad (12)$$

The relative standard deviation is

$$s_t = T \sqrt{\left(\frac{s_y}{y}\right)^2 + \left(\frac{s_x}{x}\right)^2}. \quad (13)$$

For the second case, $GLC = GLS$ ($T = 0$ percent), equation (4) is rewritten as

$$x = \frac{GLC}{z} \quad (14)$$

$$y = \frac{GLS}{z} \quad (15)$$

$$z = GLB - GLS. \quad (16)$$

The absolute standard deviations of the ATLAS variables are used by

$$T = x - y \quad (17)$$

$$s_z = \sqrt{s_{GLB}^2 + s_{GLS}^2} \quad (18)$$

$$s_x = x \sqrt{\left(\frac{s_{GLC}}{GLC}\right)^2 + \left(\frac{s_z}{z}\right)^2} \quad (19)$$

$$s_y = y \sqrt{\left(\frac{s_{GLS}}{GLS}\right)^2 + \left(\frac{s_z}{z}\right)^2}. \quad (20)$$

The relative standard deviation for this case is

$$s_t = \sqrt{s_x^2 + s_y^2}. \quad (21)$$

For the third case, $GLB = GLS$, and the transmittance value is undefined; therefore, the error estimate S_T is also undefined.

A series of figures (2, 3, 4, and 5) is presented to show an input image, the resulting transmittance map, and the error map. The processing involves the application of equation (4) to each pixel in figures 2 and 3 to arrive at the map of figure 4. Each pixel in this series of images is processed with the error algorithms previously discussed to arrive at the error map of figure 5. An appreciation of the amount of processing required for a typical trial of 10 min duration is gained when it is realized that an 8-frame running average of the base video rate of 30 frames/s is performed, and every third frame is grabbed to provide 10 frames/s (low-pass filtering) for ATLAS processing, resulting in over 6000 images for further analysis.

In summary, if the basic ATLAS algorithm, equation (4), becomes modified, the error analyses must be updated. For example, when the imager is used to observe a target of opportunity or when a source is placed in the field of view (as is the case when the VORTEX* system [11] is implemented) and the Multipath Transmissometer Radiometer algorithm is used, a new set of equations must be developed. If any of the basic assumptions are violated, the output of the error analyses is meaningless.

*VORTEX is an acronym for a transmissometer system consisting of an imager as a receiver and an array of sources configured on a tower so that multiple LOSs in the vertical dimension (as opposed to the more usual horizontal dimension) may be measured.

2.5 Mitigation Efforts

Efforts to mitigate violated assumptions or lessen the impact of the limitations have primarily only reached the discussion stage because it is felt that mitigation efforts may be so intensive at this stage of ATLAS development that they would unnecessarily slow progress and delivery of the product to the customer. However, what has been discussed, accomplished, or is in progress will be presented next.

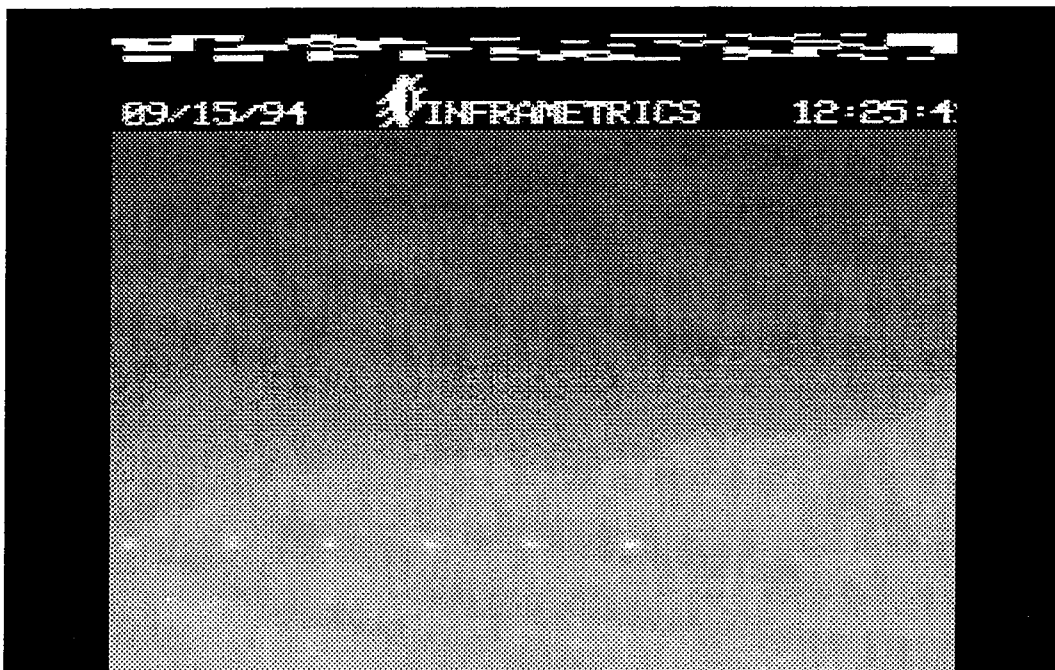


Figure 2. A pretrial image from a typical smoke trial. This scene provides the GLB used in the ATLAS algorithm. Each pixel location provides its unique grey level.

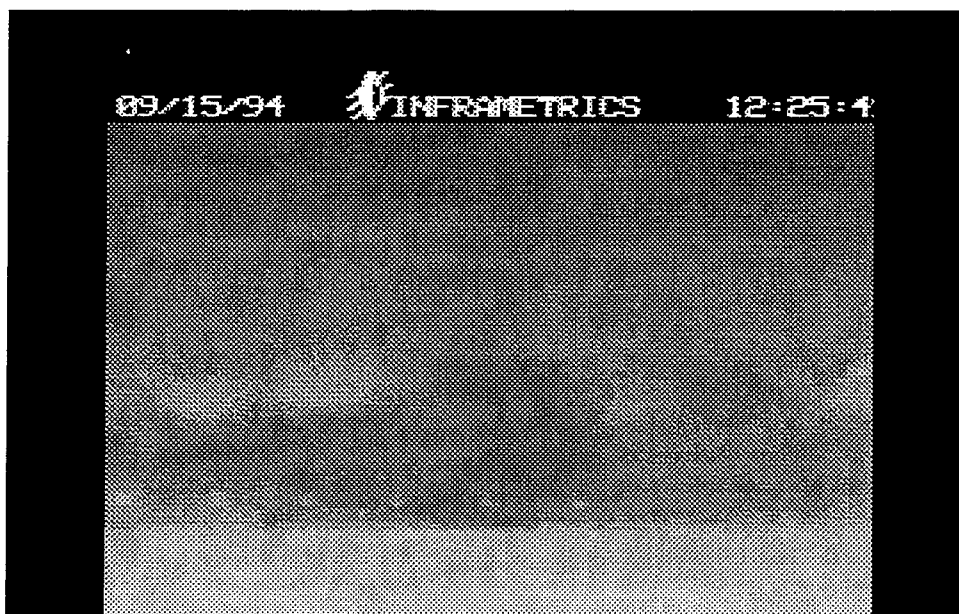


Figure 3. An image of the scene of figure 2 with smoke present. The grey level array provides the GLCs for equation (4).

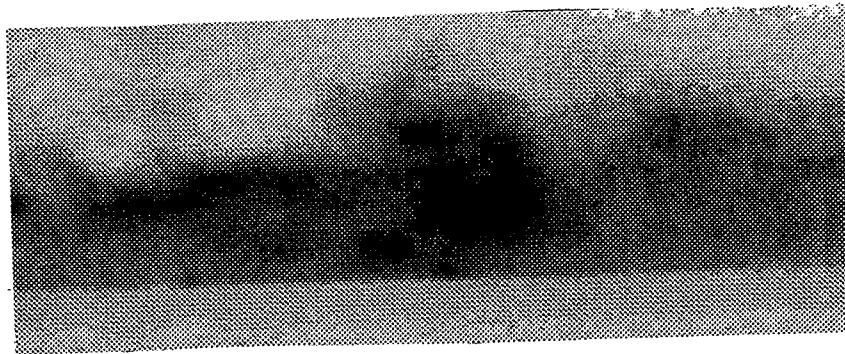


Figure 4. The transmittance map (transmittance in percent is proportional to grey level -- 0 percent is black and 100 percent is light grey) that results from the ATLAS processing of the images in figures 2 and 3. The cloud grey level, GLS, is a global constant and the same value applies everywhere in the image; therefore, there is no GLS image to correspond to those for GLC and GLB.

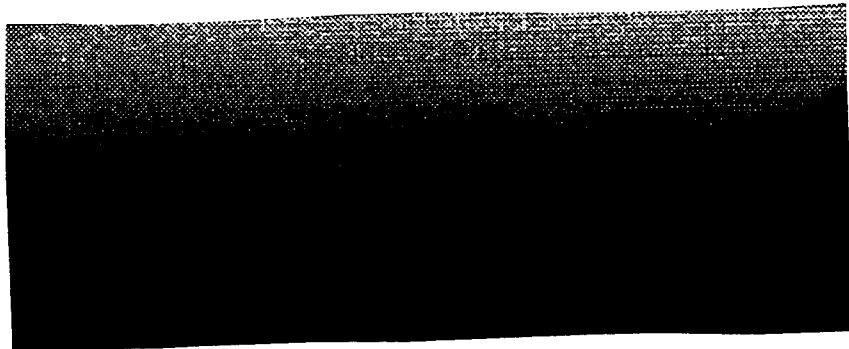


Figure 5. The error map that results from the application of the error analyses to this example shown in figures 2, 3, and 4. (Black is 0 percent error and white is equal to or greater than 243 percent error.) In theory, such a map should be provided with each transmittance image; in practice, only regions of large uncertainty are identified at the current time even though the capability exists to do the full analyses.

Two efforts are under way to understand and mitigate the limitation imposed by the temporal variation of the background radiance. To begin with, experience in the field has indicated that this may not be as severe a problem as one might think. On days of variable cloudiness, for example, the background radiance changes and instances of rapid fluctuations were observed; with no apparent cause. An example of this last situation is given by figure 6, which is a plot of grey level with time for a portion of a background scene observed in 1989. This observation was made under the following conditions:

- Time of day was approximately noon.
- Skies were clear (no clouds or haze).
- Location was Oscura Range (\approx 7000 ft elevation) (White Sands Missile Range (WSMR), NM).
- Transmissometers were positioned along the LOS.
- Visible videos in black and white and color were recorded.

From these conditions and observations (transmissometers and video observations indicated no changes from clear air conditions at the location with high altitude and clear, dry air at WSMR) it was concluded that there were no atmospheric fluctuations that could have caused the variation in background radiance. In addition, the variations were seen only in a portion of the image; therefore, it was not an imager problem. It is believed that the wind blowing up an arroyo caused changes in the transpiration and/or orientation of leaf structure of the vegetation, which caused a change in apparent radiance. In an attempt to better understand this type of problem and to assess its importance, a program of monitoring a local background scene at WSMR has been in place for about one and a half years. As part of this program, an environmental survey of the scene was conducted, and the tools necessary to reduce and understand the observations were obtained and developed. Two publications were produced by the effort. [12,13]

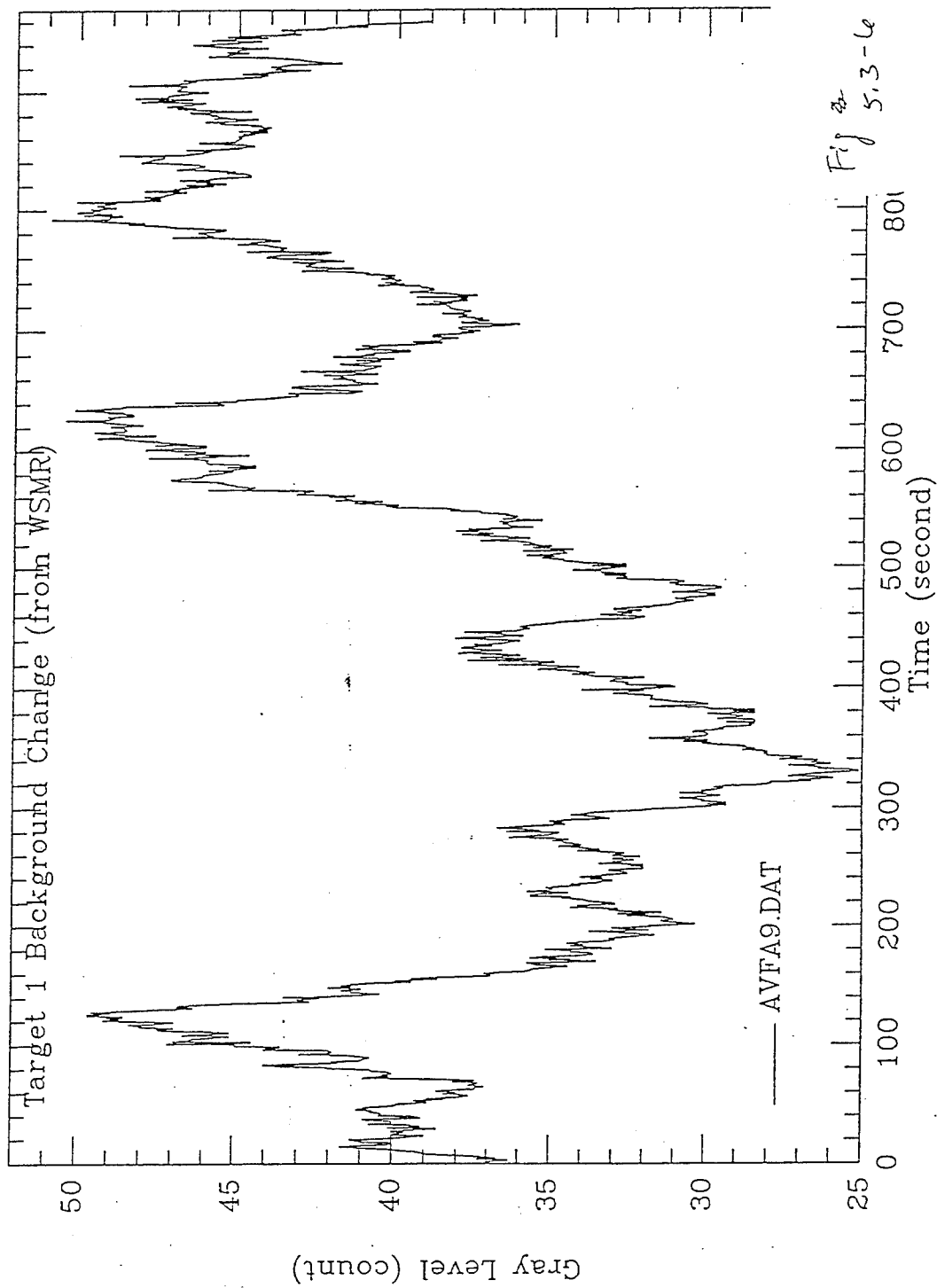


Fig 5.3-6

Figure 6. Rapid and large fluctuations in background radiance.

The other effort to mitigate variations in the background radiance is to use a millimeter wave (MMW) imaging system to observe the background radiance through visual and IR smokes and obscurants (note variations in radiance at MMW frequencies) and use the equations and models discussed to correct the IR radiance. This would serve another purpose; the imaging system could be used for ATLAS processing of MMW obscurants. The progress with this effort has been slow because of priorities. The receiver components and an antenna sufficient for single LOS observations were obtained and assembled. The next level of effort is to develop a scanning system for the radiometer so it can operate in an imaging mode. When fully developed, this system and follow-on systems will be useful for conducting scene radiance studies at MMW frequencies, characterizing MMW smokes and obscurants, and developing inclement weather surveillance systems. (Such systems could be placed in remotely piloted vehicles.)

Cloud radiance problems manifest themselves in two ways: in the determination of GLC and in which GLC is the same or nearly the same as the background radiance. The determination of GLC relies on a variety of intensive and interactive techniques. Efforts are underway to analyze the library of GLCs acquired to date to determine whether a more successful way of arriving at GLC, *a priori*, may be found. The problem of dynamic range $GLC \approx GLB$, may be overcome through judicious use of high-gain measurements; although, this will not work in all cases. A way around this is to estimate transmittance values in the region of uncertainty by using values from a nearby region and taking into account cloud movement; cloud structure remains sufficiently unchanged over small changes in time. As the situations that create this problem are better understood, test setup can be modified to eliminate the problem (observing from a different perspective to allow a different background).

When it is known that for a particular observation situation that scattering of environmental radiation by the cloud will affect the measurement, or that the cloud is self-emissive, use of sources in the field of view (see the VORTEX system description [11]) can allow modified ATLAS measurements. Use of VORTEX may allow a quantitative estimate of these effects so the error estimates may be properly made. Multispectral observations may identify scattering phenomena and, thus, assist in mitigation. Most of this is purely speculative; however, it holds promise for further development of ATLAS.

3. Conclusions

It has become more usual to discuss verification, validation, and accreditation, in particular, as applied to models. A presentation given at a recent Smoke/Obscurants Symposium, [14] defined these words to mean the following (paraphrased):

verification: Does the model do what is expected; is arithmetic correct?
(happens first)

validation: Does the model replicate what goes on in nature; how close?

accreditation: Stamp of approval by the organization using or making the model that it has been verified and validated for a specific application and the conditions for which it was verified and validated.

In the context of what is presented in this report, all three of these processes have been completed and are documented here and discussed without discrimination as to the specific category (verification, validation, or accreditation) under scrutiny. The reason for using validation in generic terms has more to do with the accomplishment of a goal than a restriction of effort. Specifically, the verification process was the work accomplished by Vonder Haar and associates. The validation is the comparison of ATLAS data with more conventional transmissometer measurements in which the differences (basically, there are none) have been quantified and reported in two of the papers listed in the reference section. [8,9] Accreditation can include the portion of the previous discussion that describes the assumptions underlying the technique and the resulting limitation that this places on the use of ATLAS.

The ATLAS technique is continually under further development. With each new test situation, more is learned and improvements are made. ATLAS has been used to support numerous field tests and has been a key measurement for characterization of smoke/obscurant clouds. The documentation presented here shows ATLAS to be a viable process of which the full potential remains to be utilized.

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Acronyms and Abbreviations

ARL	Army Research Laboratory
ATLAS	Atmospheric Transmission Large-Area Analysis System
CSU	Colorado State University
IR	infrared
LOS	line of sight
MMW	millimeter wave
WSMR	White Sands Missile Range

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