REMOTE ATMOSPHERIC VISIBILITY MONITORING RAVM

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ABSTRACT

Test ranges need advanced knowledge of visibility conditions to increase the robustness of the test data collection and evaluation process. For any given test, the ability to capture high-resolution performance data of aircraft using ground-based film theodolites and electro-optical imaging sensors is subject to uncertainties in imaging capability permitted by the intervening atmosphere.

The Remote Atmospheric Visibility Monitoring (RAVM) project is being developed as a suite of three collocated optical sensors that measure the components of atmosphere-induced image degradation. When the component measurements are combined, a 'transfer function' is obtained that can project the quality of imaging data without an aircraft being present. The resulting predicted imagery provides valuable pre mission information that can be analyzed and reviewed before incurring expensive field-test operations.

The RAVM project is a Phase II Small Business Innovation Research (SBIR) program that is developing an instrument for providing an atmospheric visibility measurement capability to support range scheduling and test operations. This advanced capability will monitor 'effective visibility' in the context of imaging extended targets, such as aircraft, and predicting the degrading effects of the atmosphere on imaging sensors operating in the visible and near-infrared regions of the electromagnetic spectrum.

INTRODUCTION

Edwards Air Force Base, California, has historically represented an excellent region for DoD test and training operations because of large airspace and good weather and visibility conditions. Since the-mid 1940s, when the facilities were established, a decrease in the visibility has been occurring. Sometimes visibility degradation is severe enough to adversely affect the optical data required for analysis of certain tests or to force changes in operational procedures or complete cancellation of a planned exercise. Degradations, if of sufficient severity, may render expensive test data useless, thus necessitating costly re-testing.

Several studies associated with this issue have been performed, including assessments of operational impacts of visibility impairment. The RESOLVE study (Ref. 1) documented baseline visibility conditions and characterizations of visibility impairment, recommended a long-term monitoring network to measure visibility trends and associated causes, and identified strategies for projecting operations.

The visibility prediction problem is difficult and in the past has been approached from several fronts; including understanding meteorology, winds, and flow patterns, developing instrumentation for particle sampling and identification at various sites, and implementing a data analysis plan. The complications arise from the fact that numerous compounds, which vary with source, observation location and time, all contribute to light scattering and attenuation; these include organics, sulfates, elemental carbon, soil, and other matter. Further, the quantity 'visibility' itself has been subject to different interpretations (Ref. 2). To utilize combinations of local point measurements and data in models to generate usable measures of sensor performance is a complicated and invalidated approach.

In fact, even if all of the atmospheric constituents, including concentrations and the variations with location were known along a given atmospheric slant path, one would then need an accurate model to determine how to combine the component effects over the optical pass-band of an imaging sensor used in any field test. Existing systems most often employ either transmissometers or scattermeters; each has its own deployment and calibration problems, and in either case, never samples the integrated lines of sight necessary for true performance determination.

The RAVM project approach is to develop a set of optical sensors, including a laser radar, whose measurements will yield a complete representation of the atmospherically degraded images seen by ground-based sensors viewing aircraft deployed at Edwards AFB, but without the aircraft being present. These can then be used to predict what the effective imaging capability of those sensors will be, including the integrated effects of all of the atmospheric constituents, as well as turbulence. The sensor suite will include an elevation and azimuth scanning capability so that image degradation over a wide field of regard, appropriate to the full spatial interrogation capability of the imaging sensor, can be measured.

TECHNICAL APPROACH

In the absence of atmospheric effects, the theoretically-limiting or vacuum performance of ground-based imaging sensors that are viewing extended targets such as aircraft depends on several characteristics. These include: the dimensions of the aircraft and the range at which it is being viewed, the aircraft's inherent contrast relative to the background, and the sensor characteristics, including its operating wavelength, aperture dimension, and its noise and threshold performance levels. The effects of the atmosphere can significantly degrade the capability of such imaging systems over slant paths of hundreds of meters or greater. Relative to the non-atmosphere or vacuum-predicted performance of a given sensor, these degradations can result in the loss of ability to detect, recognize, or identify aircraft of interest at long ranges. These degradations are usually expressed in terms of the apparent visibility of an object as seen by an optical sensor.

The atmospheric constituents that degrade the vacuum performance include naturally occurring molecules and aerosols, such as water droplets producing fog and haze**,** as well as pollutants and temperature fluctuations associated with atmospheric turbulence. The image degradation mechanisms associated with these constituents include: the change in brightness of the aircraft relevant to the sky background (i.e. the apparent contrast relative to the inherent contrast); the attenuation of the light from the aircraft to the sensor; and image break-up, dancing, and blurring due to atmospheric turbulence.

For angularly large targets, contrast reduction is generated by both the attenuation of light from the object to the sensor, as well as target masking due to light scattered into the imager from the intervening atmosphere. These two effects depend on some common parameters (e.g. particle size distributions), as well as some different parameters (e.g., solar angle), and hence both the background radiance and atmospheric attenuation must be determined.

For angularly smaller targets, turbulence and the sensor imaging characteristics combine to yield the limiting angular resolution obtainable. For a specified target and angular dimension we obtain the number of resolution elements over the target, which then permits us to determine whether we can detect or identify it. Atmospheric turbulence will cause the image to possibly break-up, dance, or blur, thus it is important to identify a technique to determine the amount of image blur along the relevant line-of-sight path between sensor and aircraft.

THE ATMOSPHERIC MTF

The general problem of imaging an extended object, such as an aircraft against a variable sky background, and in the presence of intervening molecules, particulates, and turbulence, appears to be complicated. However, it has been shown (Ref. 3) that a quantity exists, called the atmospheric modulation transfer function (MTF_A), that is precisely the function needed to 'transfer' a non-degraded or vacuum image to one that has been degraded by the atmosphere. This quantity includes the effects of molecules, aerosols, and turbulence, and yields the prescription for analytically combining these quantities to compute the contrast attenuation and the image blur of an aircraft image as degraded by the atmosphere.

The total atmospheric MTF can be written as

$$MTF_A = \mathbf{T_A} \times \mathbf{MTF}(\text{Turb}) \;/\; [\, 1 + 4\pi \mathbf{B_P} / E_o \, \mathbf{T_A} \,]. \quad (1)$$

The three bold-faced light scattering quantities required to predict the image degradation are

1) The sky-background radiance [$\mathbf{B_p}$]
2) Light attenuation from the aircraft to the sensor [$\mathbf{T_A}$]
3) Image blur [**MTF**(Turb) = Spatial Fourier Transform of Point Spread Function PSF(Θ)].

All of the parameters in Eq. 1 must be known or inferred from the RAVM sensors or supporting background measurements to predict the atmospherically degraded image. In Eq. 1, MTF (Turb) is the modulation transfer function due to atmospheric turbulence; perhaps more physically, it is the spatial Fourier Transform of the image of a point source located at or near the object, collected by an imaging camera located near the imaging sensor. It is preferred to make an optical measurement with an appropriate sensor than to predict the results from thermistor measurements, which are themselves uncertain, as are any point measurements, to predicting the integrated path resolution loss along a line of site. From Eq. 1, the measured image blur from a point source, or point spread function (PSF) is precisely the quantity needed to insert in Eq. 1 (or its Fourier Transform), and predict the image degradation.

Analysis of the atmospheric MTF reveals that one important quantity to be monitored is the path-integrated extinction coefficient between sensor and aircraft. While there are numerous visibility instruments on the market, such as transmissometers and forward scatter instruments, most only perform their sampling within a close proximity (hundreds of meters) from the light source illuminating the particles, and hence only give local values of the attenuation coefficient. Such measurements would all fail to predict atmospheric effects over inhomogeneous paths of several kilometers.

DESIGN APPROACH

The basis for the RAVM design has been to identify the required characteristics of the three component sensors that yield the information necessary to infer the distortions, have their data products linked, yet have the system be accurate, rugged, user-friendly, compact, and affordable.

The specific kinds of sensors needed have been developed from an analysis of the propagation effects shown in Figure 1, which illustrates the light scattering paths that degrade the image. This figure shows, among other features, an aircraft against a sky background. There is an inherent contrast of the aircraft against the sky that depends on the brightness of the background sky and the aircraft itself.

The three sensors required to predict the degradation are: a calibrated radiometer/camera that will measure the sky background over the spectral band of the deployed imaging sensor, and over the field of regard; laser radar (lidar) used in conjunction with a calibrated retro-reflector to generate a map of the atmospheric transmittance loss; and a second lidar, but used in a 'Guide-Star' mode to determine the turbulence-induced PSF, which is then convolved with the aircraft/object image to yield total image blur. These sensors are discussed in order below.

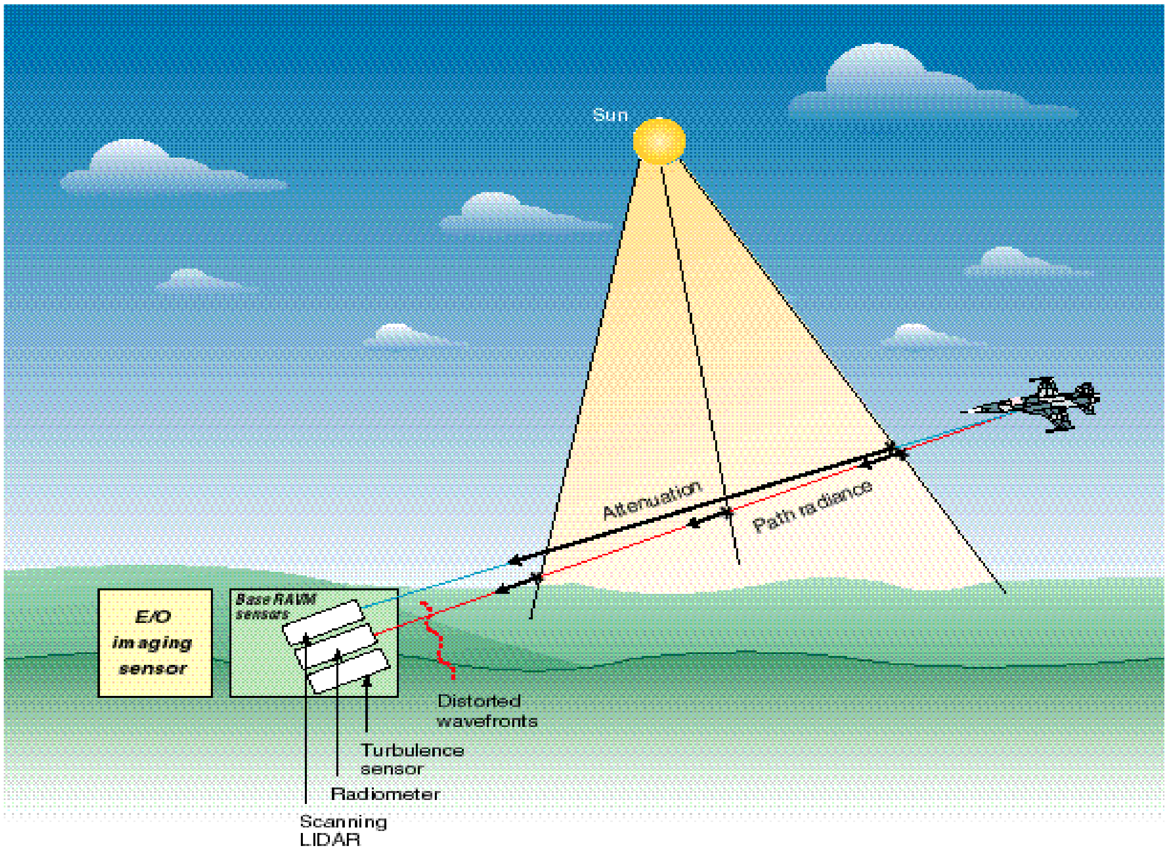

Figure 1 Remote Atmospheric Visibility Monitoring (RAVM) System Approach.

SKY-BACKGROUND INSTRUMENT

This instrument is intended to measure the sky background radiance over the angular region that the aircraft is intended to fly relative to several ground-based imaging sensors. The simplest such instrument is a digital camera with a wide field of view lens. However, the dynamic range of radiance levels on a clear day when the sun might be contained within the field of regard is over six orders of magnitude. To make accurate radiance measurements and still accommodate this large scene radiance variation, the RAVM background sensor will include a digital camera with a fish-eye lens and a sun block, and a down-welling irradiance sensor. Both instruments will be calibrated against the same source, and with the outputs combined, the fraction of down-welling radiation coming from any direction can be determined.

ATTENUATION COEFFICIENT SENSOR

This instrument is a range-gated lidar. A lidar is a 'single-ended' instrument, with collocated transmitter and receiver, eliminating the need for additional personnel and/or receiver stations. The time delay between when a given laser pulse is emitted and the time(s) when the receiver makes the measurements allows us to determine the (earlier time) pulse ranges in the atmosphere. An azimuth-elevation scanner will permit mapping of the three-dimensional region in the atmosphere, within a radius estimated to be in excess of 10 km from the transceiver location. A reference-calibrated target will be placed within the lidar field of regard and the signal reflected from this target will be used for normalization and calibration during field-testing. Also, the wavelength is chosen such that it will yield the total attenuation loss due to all of the dominant aerosol components along the path.

TURBULENCE INDUCED IMAGE BLUR

This instrument should measure the turbulence-induced spreading of an angularly small spot, which is at the approximate location(s) of where the aircraft would be at a future time. The RAVM approach to performing this measurement is an offshoot of the Guide-Star technique developed by Fugate, et al. (Ref. 4), at Phillips Lab. The basic Guide Star technique is to generate a small spot in the atmosphere with a laser, bounce this beam off of atmospheric aerosols - which will create a point (or small spot) source in the sky at the desired location, and then to measure the angular blur of that spot with a ground-based gated imaging sensor. For the RAVM problem, this means that the point spread function inferred from the Guide-Star is the same as that which would have been produced from a point on the aircraft, and we can use the measurement to infer the image blur.

DATA ANALYSIS AND PRODUCTS

Software will combine the outputs of the RAVM sensors and compute the total MTF_A. Additional software will combine the object, sensor, and $MTF_{A,}$ and produce the total image plane MTF; this quantity is the Fourier transform of the actual degraded image seen by the sensor. The software will also calculate the highest angular frequency resolvable by the system, which will determine the limiting resolution, in meters, at the object range. The software will then Fourier transform the image plane MTF, and generate actual degraded simulated images of the target, such as they would be seen by the sensor during flight testing. The software will also predict the ranges at which object detection, and object identification are possible.

The data products that will be presented include the following:

For given look directions relative to the sensor:
- The maximum range at which aircraft detection is possible.
- The maximum range at which aircraft identification is possible.

For given aircraft coordinates (i.e., range, azimuth, and elevation) relative to the sensor:
- The aircraft contrast relative to the sky background.
- The number of (atmospherically limited) resolution elements on the aircraft.
- A simulated image of the aircraft.

As an example of the image simulation data product obtainable from RAVM, Figure 2a shows a frame from a video of a simulated scene of an aircraft and bomb drop as observed from two different angles, but without atmospheric effects. Figure 2b illustrates the incorporation of both camera and atmospheric effects on the two images, such as might be inferred from the RAVM sensor suite. In this second figure the aircraft can be seen but is difficult to identify, and the bomb is barely resolvable. If the atmospheric transmission were a little worse or the turbulence was greater, then the bomb would not be resolvable.

Figure 2a Sample frame from video simulation

Figure 2b Scene of Figure 2a with system and atmospheric MTF applied

CONCLUSION

The Remote Atmospheric Visibility Monitoring (RAVM) project will produce a modular suite of sensors for determining the total atmospherically limited visibility of distant objects. Advanced knowledge of the atmospheric-limited visibility of distant aircraft and other objects is of interest to several government and commercial organizations. The projected capability of the RAVM system would be a significant enhancement to traditional weather monitoring stations for use at commercial and military airports. Such an instrument could increase the utility and safety afforded by weather stations, as well as airport control centers.

An additional user community consists of those federal and commercial organizations interested in simulations. An increasing number of organizations are getting into the image simulation business, because of cost efficiencies obtained relative to actual field-testing. Most organizations do not include atmospheric effects into their simulators. Once the RAVM method is confirmed against actual imagery, the incorporation of a validated atmospheric effects interface module could be used to support a more accurate simulation capability.

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