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FIRST REMOTE MEASUREMENTS OF SMOKE ON THE GROUND AT NIGHT

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1. INTRODUCTION

Fire is recognized as a fundamentalecological process in many forest and rangeland ecosystems throughout the U.S. Ecosystems depend upon fire for health, reproduction, and protection from invading species.

The Southern States are leaders in using prescribed fire and understanding its effects. Approximately 200 million acres of forest land are found within the thirteen states that make up the South - states roughly south of the Ohio River and from Texas eastward. Though these states have about 24 percent of the land area, they comprise 40 percent of the forest land in the United States.

From 6-8 million acres per year are treated with prescribed fire. Southern land managers have found that prescribed fire can economically reduce fuels, remove species that compete for nutrients, enhance habitat of endangered species, and lower danger of wildfires that can destroy fragile ecosystems, reduce commercial fiber and threaten urbanized areas.

2. THE SMOKE PROBLEM

However, where there is fire, there is smoke. The effects of prescribed fire on air quality are a serious concern. Visibility reductions caused by smoke or a combination of smoke and fog have been implicated in multiple-car pileups, numerous physical injuries, heavy property damage, and fatalities. As population increases and the numbers of travelers on the nation's highways increases, the number of accidents related to smoke and fog can only be expected to increase.

The mild, mostly snow and ice free winters make the southern and southwestern climate ideal for the development of retirement communities. Thousands of older people, many with respiratory problems, have relocated into these communities. Many of these retirees have little or no experience with forestry practices and therefore may not be receptive to frequent Incursions of smoke into their communities

God cannot be sued Catastrophic wildfires. whether natural or man-caused. are considered as "acts of God." Man can be sued Agencies can be sued for damages implicated by smoke or face costly stop-action injunctions that waste resources and lose favorable weather opportunities for prescribed burning. Furthermore, it may be easy to motivate a public to take precautions in the face of smoke from a monster fire. Public cooperation may be harder to come by during smaller, seemingly insignificant and more frequent prescribed burns that can produce locally serious smoke incidents.

Land managers face a dilemma. They must treat forests more frequently with prescribed fire to reduce wildfire threat to nearby dwellings while increasing the threat to air quality or they may preserve air quality by not burning and increase the threat of destructive wildfire. Thus. once prescribed burning becomes a widespread practice, the wildland/urban interface problem will become one of both fire and smoke.

3. SMOKE MOVEMENT AT NIGHT - A CRITICAL PROBLEM

Existing information on smoke, particularly the behavior of smoke at night, is largely anecdotal. The body of scientific information necessary to serve as a base for wise management decisions and sound regulatory guidelines is lacking. Mistakes made at one location can lead to unnecessary penalties imposed on prescribed burning at other locations.

Although smoke in the daytime can be a nuisance when it moves into sensitive areas and a hazard to transportationwhen it drifts across roadways, the most severe Impacts of smoke near the ground occur at night. Small amounts of smoke from smoldering heavy fuels can become trapped near the ground and carried several miles without much dispersion. In addition. smoke entrapped within moist shallow valleys can initiate or enhance local fog. Visibility impatrment by smoke or smoke/fog over roadways can create serious hazards to transportation.

That the deleterious smoke/visibility conditions occur is well known. The real challenge to forest managers is knowing when and where those conditions will occur. The real challenge to smoke modeling is receiving information in a timely manner and processing it in a way that forest managers can use to

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make meaningful decisions regarding burn operations and/or post-burn smoke monitoring.

Beginning in late 1990, Forest Service scientists at the Southern Research Station launched an effort to pose the smoke issue as a scientific problem. A solution to the smoke problem would have to answer three questions: a) Where does the smoke go? b) How much gets there? c) What kind is it? If a satisfactory answer could not be found for the first question, there was no use in proceeding to answers for the second and third questions.

Acomputer-driventime-dependentnumerical wind model called SNAF for Slow Nocturnal Wind Flow was developed to answer the first question (Achtemeier, 1991, 1993a). The model was required to have a nigh resolution in order to simulate airflow through road and stream cuts and through narrow gaps in ridges characteristic of the terrain of the Piedmont of the southeastern United States. The model was also devoted to detecting important weak winds - winds generally less than 1 m sec^{-1} that register as calm on National Weather Service instruments. During a typical IO-hour nocturnal period, a wind of 0.5 m sec^{-1} will carry smoke 10 miles (16 km). That's enough to bring smoke across a roadway in most areas of the South. SNAF was tested with measurements of winds at a hillside location near Macon, GA (Achtemeier. 1993b, 1993c).

A second numerical model that generates and follows the course of particles was developed to simulate the movement of smoke. Then, to improve on diffusion and dispersion at these very slow wind speeds, the particles periodically give birth to "daughter" particles which can be carried away in diverging air currents (Achtemeier, 1994). The concept of a multiplicity of particles or "bubbles" having been birthed from existing particles, gave rise to the name "Pregnant Bubbles". Pregnant Bubbles was combined with SNAF to produce slow wind & particle dispersion model that retained the name, Pregnant Bubbles.

The concept of Pregnant Bubbles was tested with a case for which smoke was implicated as a factor in an accident in western Georgia on October 20. 1986 (Achtemeier. 1993d, Achtemeier and Paul. 1993, 1994). This area of the Piedmont is cut by numerous streams. Elevations between stream basins and ridge tops ranged from 80-150 ft (25-45 m). With actual weather data as input, Pregnant Bubbles simulated smoke movement near the ground from just before sunset on October 19 to 0700 EST on October 20. The model correctly placed smoke at the accident site at the time of the accident and also at the site of an observer on a different road at the time smoke was observed.

The tests with SNAF at a hill site near Macon, Georgia, and with Pregnant Bubbles at a site in western Georgia, proved the concept of Pregnant Bubbles in an extremely limited way. The model generated complex wind fields and smoke patterns over a wide area and there were only a handful of observations at a few locations and times. Even though the tests were successful, there remained an unanswered question, "How accurately does the whole field of bubbles match with the smoke plume?" Clearly an answer to this question is not possible without the ability to observe the smoke plume in its entirety.

4. REMOTE SENSING SMOKE AT NIGHT

The only way to observe a smoke plume moving near the ground at night is from the air. It was hypothesized that the smoke that scatters headlights from vehicles to create visibility hazards would also scatter moonlight and thus be visible from the air.

During January-March 1997, a project was conducted to test if smoke could be observed from an aircraft equipped with a light-enhanced video imaging system. The project Included representatives from the USFS Remote Sensing Applications Group (RSAG), Region 8 Fire and Aviation, and the Southern Research Station Smoke Management Team. The project was held at the Oakmulgee Wildlife Management 4rea located on the Talladega National Forest in western Alabama. The site was selected because:

(1) Valley to ridge elevation differences were typical of the Piedmont (200-300 ft; 60-100 m).

(2) Major stream valleys extended 10 mi (16 km) without crossing important roadways.

(3) A major highway located 8 mi (13 km) from the site was separated from all drainages by a system of ridges.

(4) Few alien light sources (yard lights, lights from homes or automobiles) were present to interfere with the light-sensitive equipment

The field operations were restricted to clear skies and near calm winds during three 8-night windows timed to coincide with the full moon in January, February, and March 1997. This approach insured data collectron during maximum moonlight. However, only four nights, one in January, one in February, and two in March met the meteorological criteria

A Xybion intensified multispectral video camera capable of amplifying moonlight up to 15,000 times was mounted in a Beech Craft King Air aircraft and flown at approximately 1,500m agl. Video imagery was stored via a super VHS data recorder. GPS tracking information was incorporated on each frame of the recording tape.

Only one night during the January window was suitable for operations. A 40 acre night burn was started at approximately 2100 CST. The heat column generated by this fire lofted smoke above the surrounding ridges and it was carried off by prevailing winds.

Though unsuccessful at remote sensing of smoke trapped near the ground, the January mission provided some useful lessons. The prescribed fire generated too much heat and lofted the smoke above the valley inversion. Alternative methods to generate much smoke without inversion-penetrating heat would have to be found. Furthermore, near infrared radiation coming from the ground and passing through the smoke exceeded moonlight reflected from the smoke. Smoke was rendered nearly invisible.

A new smoke-generating method was designed using smoke bombs and hay bales soaked with diesel fuel. A visible light bandpass filter (hot mirror) was employed to cutoff near infrared light and improve spectral contrast between smoke and background terrain features. Then, during the February operations window, the equipment was mounted and tested in a 100 ft tower located on the Oconee National Forest in Georgia. The smoke source was a single bale of hay soaked with diesel fuel and ignited. Once burning vigorously, the fire was extinguished. The smoldering hay produced copious amounts of smoke with minimal heat production.

During 20-21 March 1997, the project returned to the Oakmulgee National Wildlife Refuge near Centerville, Alabama. Forest Service ground personnel burned 50 bales of hay soaked in diesel fuel. In addition, they detonated 60 smoke bombs that had a burn lifetime of approximately 2 minutes each. The fire was started at 2145 CST along a road that followed a NE-SW oriented stream basin (Fig. 1).

Aircraft overflights at approximately 1,500 m agl commenced at 2148 CST and continued at 7 minute intervals for two hours. Video images from the Xybion intensified multispectral camera equipped with the hot mirror were stored in SVHS format.

Images from the SVHS tape were captured using a TARGA-Plus frame grabber. These images were stored as TIFF image files in a OPTIMAS image analysis system. In the OPTIMAS system the images were spatially calibrated using the altitude of the aircraft and the field of view. This method was tested from known images and altitudes of an airport runway. Once the calibration was verified, a test was performed by using ground references such as a flashing light at the intersection and known road locations determined from differential GPS values. The coincidence of known GPS positions and the OPTIMAS positions were compared graphically. Any displacement between the two were corrected by an x-y coordinate shift.

The above procedures were used because 1) aircraft geoposition was not differential GPS and therefore our georeferencing was approximate, not absolute, and 2) we had no data on aircraft crab, roll, pitch, and yaw and therefore could not be certain that the camera was always pointed vertically to ground.

It was necessary to enhance the contrast of the image. The contrast was stretched using an output lookup table.

5. RESULTS OF EXPERIMENT

Figure 1 shows enhanced images of the first successful remote imaging of smoke near the ground at night done on 20 March 1997. The field of view is 1400 m in the horizontal and is compressed to 1050 m in the vertical with an aspect ratio for analog video of 1.335.

The burn site is identified by the bright area near the top of Figure la. The bright area was smoke illuminated by a combination of scattered moonlight and diffused light from flaming material. The valley road leading from the lower left of the image to the burn site is clearly visible. Other roads follow ridge lines; one to the west of the burn site and the other barely visible to the southeast near the right edge of the image. These roads connect south of the burn site thus enclosing the drainage area. The drainage area exits past the burn site toward the top of the figure.

The origin of the secondary sources of reflected light surrounding the burn site and extending toward the bottom right of the figure are not known for certain. The sources could be bare ground beneath hardwood trees that had not yet leafed-out. Roads are visible as strips of bare ground. In addition, dogwood trees were in full bloom. Dogwood blossoms reflect in visible light. Ground observers reported that flowering dogwoods could be easily seen in moonlight.

By 2202 CST (Figure lb), the smoke plume has moved up the valley along the valley road. Although the brightest areas extended from the burn site toward the center of the image, dense smoke was observed all along the road to where it ascended the southern ridge of the valley near the bottom of the image.

After 2215 CST, the smoke turned up a side valley and crossed the southern perimeter road. An example is the image for 2258 CST (Figure Ic). Elevations surrounding the drainage basin were above 480 ft (145 m) except at one location where they were 430 ft (130 m. It was at this location where smoke exited the valley.

The pattern of smoke movement continued through 2300 CST. Figure Id (2351 CST) shows smoke shortly after the burn was concluded. The bright areas at the burn site were vehicle headlights. T a dissipating smoke plume continued to flow up the side valley. The image shows no evidence of smoke along the lower half of the valley road. Ground crews reported dense smoke along that stretch of road however.

6. DISCUSSION

The Talladega Smoke Study has revealed the following:

(1) We have proven a technology that uses an intensified multispectral video camera for

airborne remote sensing of smoke moving near ground at night. This technology is critical for smoke management because airborne observations are the only means by which the movement of the entire smoke plume can be observed, hence understood, and the only source of observations adequate to validate numerical models for ground-level nocturnal smoke movement and dispersal.

(2) The windfield near the ground at night is extremely complex in both space and time. Winds are channeled by small variations in elevation. Therefore, smoke within such windfields can be carried to unexpected places. This points to a need for a smoke sensing technology that can be used routinely under starlight as well as moonlight to monitor smoke movement at night.

(3) A comparison of ground observations with smoke images collected from the airborne remote sensing part of the Talladega project revealed that some shallow layers of dense smoke escaped detection. Some smoke was hidden beneath partially closed vegetation canopies. However, we noted the apparent absence of smoke over the southern half of the valley road in the imagery. Furthermore. smoke that turned up the side valley and crossed the gap in the ridge vanished from the imagery. It was passing over a clear-cut field and should have been clearly visible.

In order to detect dense smoke confined to shallow layers, it is necessary to increase the sensitivity of the intensifier from 15,000 to 75,000. Then the video camera should be outfitted with filters that pass only blue and ultraviolet wavelengths, wavelengths that are scattered mostly by smoke.

Successful widespread application of prescribed fire will require knowledge of smoke concentration, location, and movement so that appropriate reaction strategies can be implemented if necessary. The Talladega experiment shows that smoke moving near the ground at night can be remotely imaged from an aircraft. Thus it may be possible to monitor nocturnal smoke events operationally. Such data will be useful for implementing reaction strategies and for validation of numerical smoke movement and dispersion models.

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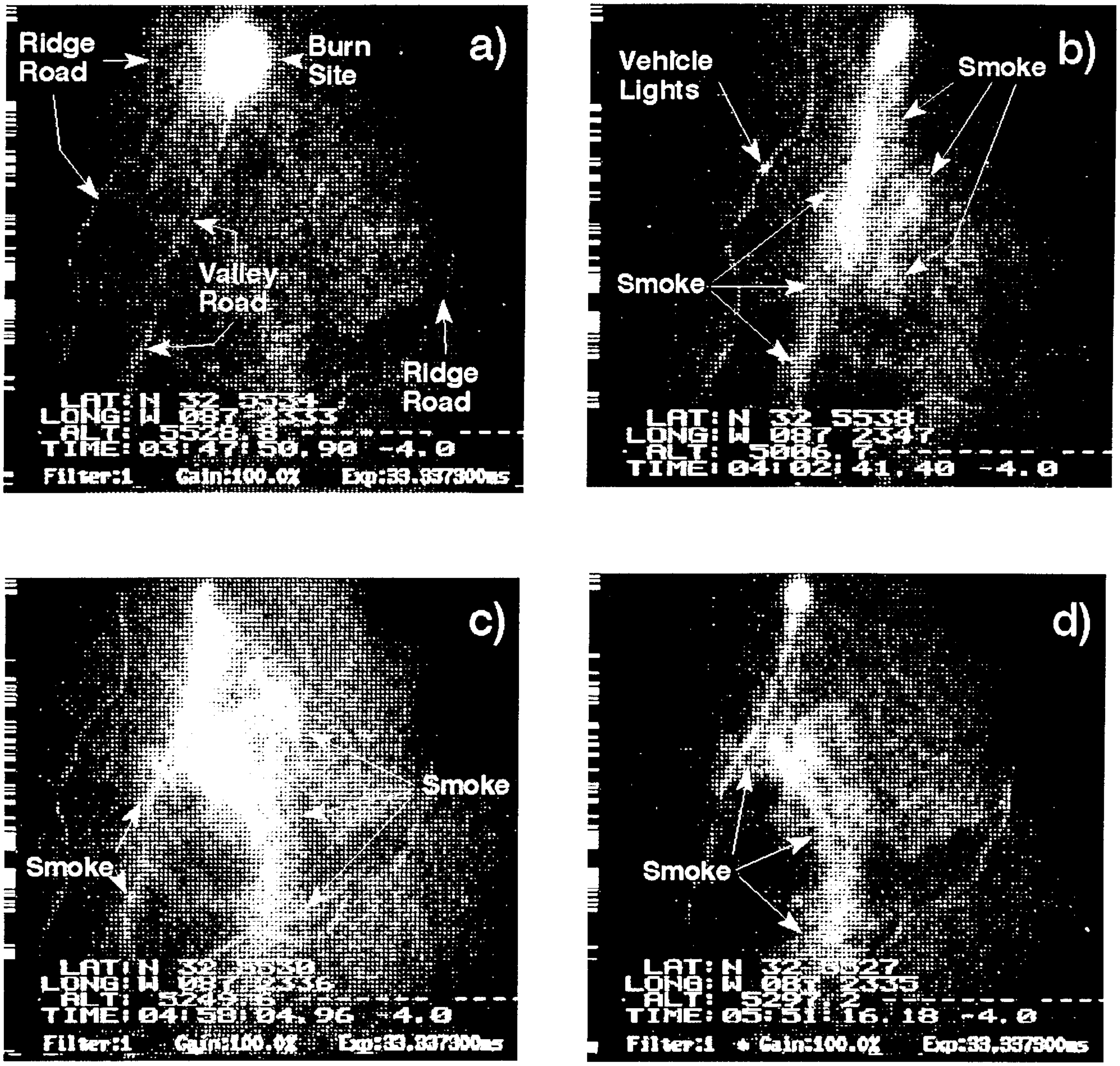

Figure 1. Images of smoke moving along the ground at night. a) 2147 CST - plume shortly after ignition, b) **2202** CST - plume drifting up valley along road, c) **2258** CST - plume diverting into adjacent valley, and d) **2351** CST - dissipating plume at end of burn.