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Multispectral Image Enhancement Reveals Kuwaiti Oil Plumes

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Abstract

Absorbing of incoming solar radiation at visible wavelengths, oil smoke is nearly invisible over water on many environmental satellite images. To improve the detectability of smoke, the authors construct bispectral composites from images from the NOAA Advanced Very High Resolution Radiometer (AVHRR). These composites are constructed from a ratio between AVHRR channels 1 and 2. While neither channel by itself shows smoke over water, the ratio image often depicts smoke quite distinctly. The authors discuss an interactive program on a computer workstation which enables even an untrained user to develop further enhancements using this ratio image.

Introduction

The ongoing proliferation of satellite receiving workstations is revolutionizing environmental remote sensing. Just a few years ago, remote sensing display workstations were confined to large laboratories and major government installations. Data handling was often cumbersome and required large centralized data reception and distribution centers. Now satellite-receiving workstations are becoming more numerous and much more self-contained. These workstations allow image enhancement and manipulation in real time. As satellite workstations become more inexpensive, they are appearing all over the world in support of geology, oceanography, meteorology, hydrology and geography.

Relatively untrained scientists and technicians in the field are now trying to perform tasks which were once performed only by experts at central site facilities. Unfortunately, when operators do not know the basic principles of remote sensing and image enhancement, even the most powerful workstations can remain underutilized. Recognizing the vast potential of these workstations, the Naval Research Laboratory is designing interactive software packages that simplify the process of image enhancement. Once implemented in the field, our workstations will enable a large variety of analysts to arrive at useful products very quickly. We apply our techniques to smoke scenes from the recent Kuwaiti oil well fires in the Persian Gulf. Our data comes from the National Oceanic and Atmospheric Administration's (NOAA) polar-orbiting satellites.

Data

The Advanced Very High Resolution Radiometer (AVHRR) abroad the NOAA polar-orbiting spacecraft has proven to be a useful tool to study the Kuwaiti oil fires.[1] Its images come from five channels, representing five wavelength intervals. Channels 1 (.63 microns) and 2 (.86 microns) measure reflected solar radiation. Channel 3 (3.7 microns) measures both reflected solar (during the daytime) and emitted radiation. Channels 4 (10.8 microns) and 5 (11.8 microns) are located within the thermal infrared region. The AVHRR has 10-bit radiometric resolution which enables 1024 distinct gray levels. The NOAA satellites provide roughly twice-a-day coverage of a given region, yielding AVHRR "swaths" in a resolution of 1.1 km per pixel at nadir.

Background

The USS Wisconsin was stationed in the North Arabian Gulf when the smoke outbreak began. An after-action report by the Wisconsin[2] discussed the conditions encountered: "The smoke, caused by Iraqi forces igniting over 500 oil wells in Kuwait, produced an ominous overcast that completely blocked out the sun between 0900 to 1600 local (time), with ceilings from 0 to 300 feet. The ceilings encountered correlated well with a weak inversion layer noted on that days (sic) sounding. The smoke persisted for several days with the most severe being 03 Mar 91 when the sun was completely blocked bringing a night like darkness to the area. Horizontal visibility at the surface remained 2 to 4 nm using night vision equipment and the ship was able to continue low level helicopter operations."

Darkly-colored smoke, such as produced from the Kuwaiti oil fires, has attracted scientific attention for several years. Of all the potential atmospheric byproducts of nuclear war, black smoke has the greatest potential for altering the earth's climate ("nuclear winter" scenario). Crutzen et al. suggests that the light-absorbing smoke would block solar radiation, causing darkness and cold at the surface of the earth.[3] Thus, the burning oil wells in Kuwait became an "experiment of opportunity" for researchers modeling the effects of smoke on regional climate.[4,5]

Oil smoke differs from other kinds of smoke, for example forest fire smoke, due to its high soot content.[6,7] The high soot (elemental carbon) content explains its black color. Soot is produced only by actual combustion, as opposed to smoldering fires.[7] Viewed from above at visible wavelengths, the black appearance of oil smoke results from its high absorptivity (low reflectivity) and high optical depths.[8] Viewed from above at infrared wavelengths, oil smoke is semi-transparent. Thus, it tends to have a similar appearance to the image background.[1]

Figure 1.

NOAA AVHRR Channel 1 on 2 March 1991. Image is enhanced, but oil smoke is difficult to detect over the Persian gulf.

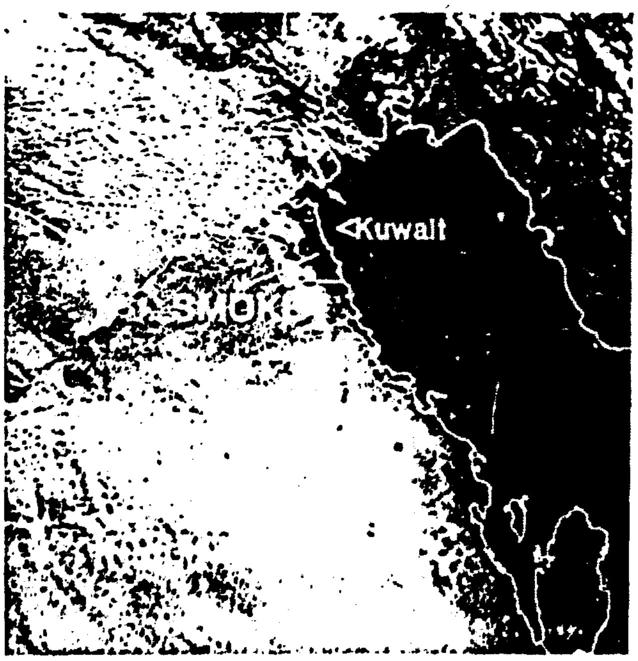
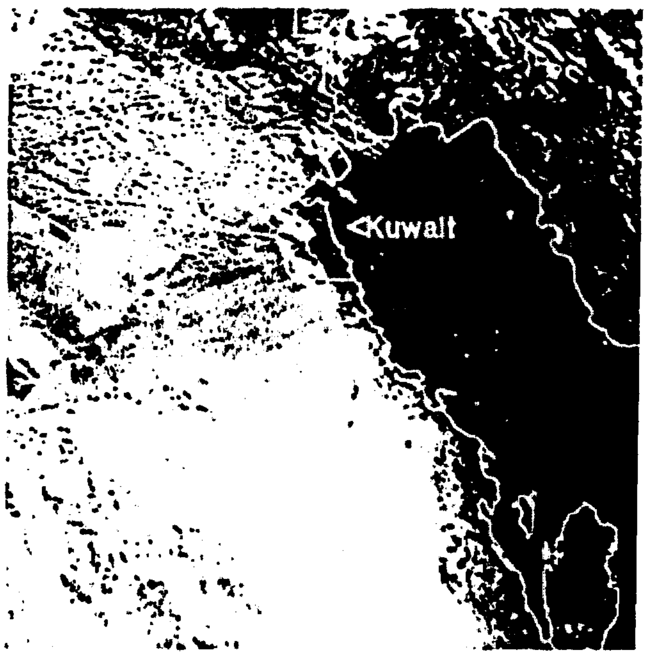


Figure 2.

NOAA AVHRR Channel 2 on 2 March 1991. As in channel 1 (Figure 1), oil smoke is not readily apparent.



Case Study

On 2 March 1991 northwesterly winds blew oil smoke into the Persian Gulf. Channel 1 is "contrast-stretched" to enhance the lower (darker) reflectance values in the scene (Figure 1). On the image the northwestern tip of the smoke plume contrasts well over the bright Kuwaiti land background. However, despite the enhancement to show the darker regions of the scene, no smoke can be seen over the waters of the Persian Gulf. This lack of contrast appears because the smoke, like the underlying sea surface, reflects so little solar radiation. As in channel 1, an enhancement of channel 2 (Figure 2) shows no trace of oil smoke over the dark sea surface background.

Channel 3 (Figure 3) shows several white spots over Kuwait, representing the heat of several burning oil fields. These hotspots, which do not appear in the longwave infrared images (channels 4 and 5), are examples of the unique ability of channel 3 to detect tiny (much smaller than a 1 km pixel) but extremely hot features.[9,10,11,12] Channel 3 hotspots, which often appear just upwind of a smoke plume, are extremely useful in the identification of many smoke plumes. Over the sea surface, channel 3 gives a faint view of the smoke plume. The elevated smoke appears in dark grayshades, indicating a radiative temperature lower than the background. Channel 4 (Figure 4) and Channel 5 (not shown) show smoke faintly over the Persian Gulf near the Kuwaiti coastline. Away from shore the plume tends to blend with the sea surface in both channels.

Figure 5 shows a pixel-by-pixel ratio of channels 1 and 2. Compared to channels 1 and 2 (Figures 1-2) the ratio image shows improved detail over the Persian Gulf, but further enhancement is necessary to detect smoke. However, not all enhancements that could be applied are equally effective or appropriate. A preset (or "canned") enhancement, designed for repeated use with a particular product, often fails to deliver consistent results over a variety of scenes. A linear contrast stretch, which allows the analyst to establish appropriate high and low display limits, can produce a higher-quality enhancement than a preset enhancement. Unfortunately, a linear contrast stretch is time-consuming, requiring experimentation before arrival at a useful product.[13] Histogram equalization (described in Rees, 1990) increases the contrast over frequently occurring gray shades and decreases the contrast over infrequently occurring gray shades. It is not useful, however, to apply histogram equalization to Figure 5 because the area of Persian Gulf is small in relation to the image as a whole and contributes little weight to the histogram equalization procedure.

Our solution is to allow the analyst, using a mouse or a trackball, to select a small sub-area within the image as an area of interest (shown on Figure 5). Then, the program performs a histogram equalization on only the data values correspond-

Figure 3.

NOAA AVHRR Channel 3 on 2 March 1991. Hotspots (small bight areas over Kuwait) mark oil fires. Oil smoke plumes are moving downwind.

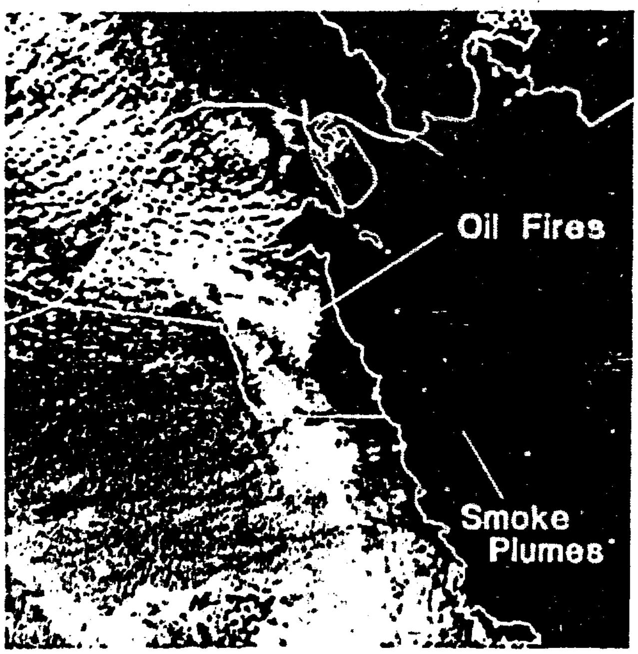


Figure 4.

NOAA AVHRR Channel 4 on 2 March 1991. Oil smoke plumes are difficult to detect downwind of Kuwait over the Persian Gulf.

ing to the subarea. Finally, it applies the resulting enhancement to the full area of the original image (Figure 6), revealing smoke plumes distinctly.

The ratio image (Figure 6) exploits the slightly different aerosol scattering properties of the shorter wavelength (channel 1) versus the slightly longer wavelength (channel 2).[14] In regions without smoke, channel 1 is more reflective than channel 2, suggesting significant channel 1 back-scattering by small, naturally occurring airborne aerosols. Where the sea is covered by oil smoke, on the other hand, the reflection received by the satellite is nearly identical in the two channels. The similarity results because smoke particles tend to be relatively large, favoring increased back-scattering at the longer wavelength. The ratio between the channels exploits these interchannel differences and produces an improved image over the Persian Gulf. Low values of the ratio (shown in bright gray shades on Figure 6) indicate smoke over the Persian. Gulf. High values (dark gray shades) indicate open water.

Discussion

Oil smoke produces fairly subtle signatures on satellite images, and no one AVHRR channel will always produce an easy-to-interpret image. The ratio image often produces dramatic improvement compared to individual channels, but even it will not always produce the optimal contrast between smoke and water. Thus, a user will often need to perform a series of enhancements. We have demonstrated an enhancement which can be performed quickly and without expertise, allowing unsophisticated analysts to arrive at useful products in a minimum of time. Such an approach is particularly valuable for field users under pressure to analyze imagery in a short period of time.

We have used the sub-area histogram equalization technique to enhance a ratio image, but the technique has broad applicability to a variety of images or image composites. This technique can also be applied to other phenomena besides cil smoke, In general, it is useful in the enhancement of any low-contrast feature which overs a small portion of an image. Ship and aircraft exhaust trails, urban heat islands, and fires are examples of phenomena which can be enhanced using this technique.

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Figure 5.

Ratio image of channels 1 (Figure 1) and 2 (Figure 2). Small sub-area over the Persian Gulf shows region of histogram equalization for Figure 6.

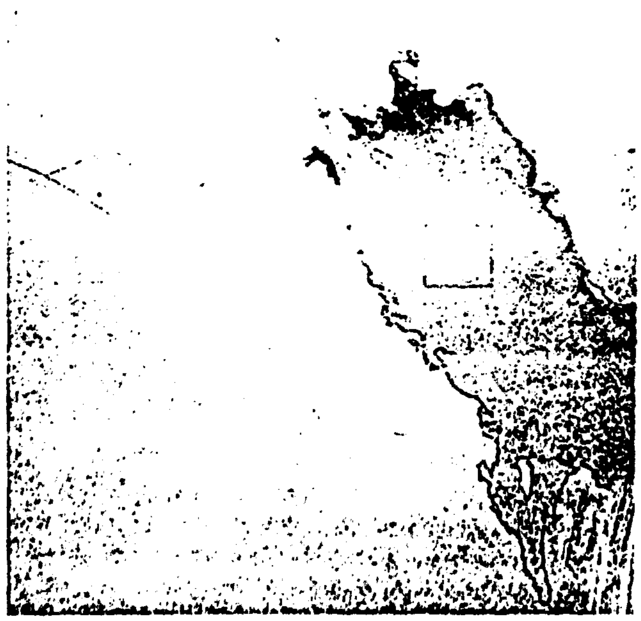
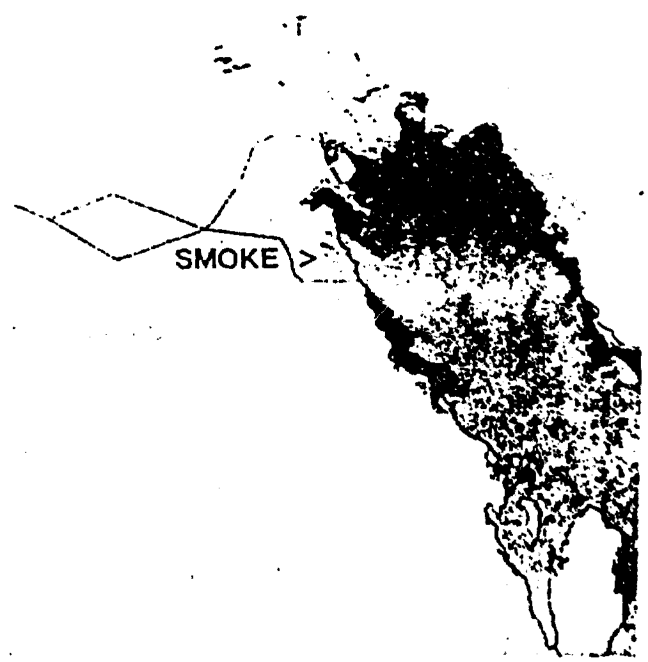


Figure 6.

As in Figure 5, after sub-area histogram equalization.



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Biographies

Thomas Lee is a satellite meteorologist who has worked on the development of meteorological products for forecasters in the field. He has published papers on the detection of aircraft exhaust trails, the analysis of airborne dust, and the classification of extreme heat sources on the surface of the earth. At the present he is researching the capabilities of passive microwave sensors to analyze marine weather patterns.

James Clark is a satellite meteorologist who has worked extensively on the development of meteorological workstations. He helped to develop a prototype Navy workstation in the late 1970's (SPADS) and is now helping to develop the Navy Environmental Operational Nowcasting System (NEONS).

Maureen Thompson currently works for the Computer Science Corporation under contract to the Navy as the database manager for the NEONS relational data base system. She has worked on various government contracts after graduating with a B.S. in meteorology from San Jose State University.

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