A NOISE TAXONOMY FOR REMOTE SENSING SYSTEMS[1]

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ABSTRACT

Sources of noise and other information degrading variations are considered and located in a taxonomy. Earth observational optical remote sensing systems are defined as consisting of three subsystems: the scene, the sensor, and the processing subsystems. Significant noise sources of each of these subsystems are then assigned to relevant noise categories. The literature is briefly surveyed for models of these sources and for studies of their independent and/or interrelated effects. Finally, a discussion is included concerning future directions and considerations in the study of noise.

Key Words: Noise, Remote Sensing Systems.

INTRODUCTION

Science can be defined as 'a branch of study concerned with observation and classification of facts and especially with the establishment of verifiable general laws.' Remote sensing has long been regarded as an art grounded in applied science with an integral part of many remote sensing projects being the skill provided by analysts in their interpretation of images. Physical science and engineering have provided the tools to gather the raw information to be processed by photointerpreters, and as well as in more recent years by analysts with the aid of computers. Recently, the technology of sensors and processing equipment has developed to the point where new system designers have tremendous choices available. With the coming of accessible space platforms and the shuttle, space sensors will be able to be designed, or possibly reconfigured, for more specific experiments or studies than previously possible. Thus, it is becoming more and more evident that remote sensing must be understood as a science in order to design systems that gather the desired information effectively and efficiently.

In developing remote sensing as a science, a comprehensive understanding of the system is a major goal. A key element of these systems is the noise, or unexpected variations, that can occur at each component of the system. Noise is important both from its effect at that component of the system where it occurs, but also from the interrelated effects it may have on other components of the system. In studying noise in remote sensing systems a need was seen for a structure in identifying the various sources of noise.

A taxonomy (or system of classification) for noise is developed here based on a general model of space based remote sensing systems. An understanding of the noise implies an understanding of the signal, or desired information. Unfortunately, due to the complex and diverse nature of remote sensing systems the division between the two is blurred, and overlap often occurs to a degree dependent on the particular study. Thus many of the entries in the taxonomy may be considered signal and noise, depending on the goal of the study. This paper seeks only to identify possible noise sources and locate them in a structure.

REMOTE SENSING SYSTEMS

The type of systems considered here are Earth observational space based sensors for the analysis of land cover, including agriculture, forestry, natural lands, and water quality concerns. This context includes a wide range of current remote sensing systems including the Landsat series and SPOT, while also including the many more application specific sensors that may be planned for deployment on the upcoming space station polar platforms.

The system is divided into three subsystems: the scene, the sensor, and the processing subsystems. The scene contains the spectral, spatial, and temporal variations of the surface reflectance and in the transmitting medium (atmosphere) which are then present at the input of the sensor. These variations include both the information bearing and information degrading types. The sensor includes all electrical and mechanical effects of transforming the incident electromagnetic wave signal into the scanned and sampled discrete electrical signal that is a representation of the scene and suitable for processing. The processing subsystem includes all effects of obtaining the desired output information of the system from the data obtained by the sensor. It may include the effects of computer processing and the influences of analyst decisions in analyzing the data.

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In each subsystem many factors contributing to the data at that point (ie. the received radiance at the sensor, the pixel intensity at the processing subsystem) can be modeled as a deterministic effect; many others are of such complexity and variability that a stochastic (Papoulis, 1984) representation is much more reasonable. An example of a deterministic effect might be the Optical Transfer Function (OTF) of the sensor, while effects better modeled as a stochastic process include the within species variation of reflectance, or the thermal noise induced in the sensor optical detectors. Thus it is recognized that any understanding of the system and its noise must incorporate both deterministic and stochastic descriptions. We note specifically that stochastic processes are useful not only in modeling random variations which are not information bearing; indeed their most characteristic property is that they are most useful in modeling very complex variations, be they contain signal or noise.

NOISE TAXONOMY

In the context of this research noise is defined to be any source or effect that occurs in the system that is not information bearing, or that even degrades the desired information to be obtained at the output. Note that this definition is dependent upon the desired information. At this point, no assumptions are made as to what information may be desired, but rather all possible noise variations are to be identified for all possible outputs, and there will be situations where effects described as 'noise' will actually be the 'signal', and vice versa.

Although the purpose of this paper is to identify and categorize noise sources, it is recognized that no list, however long, could exhaustively describe the various sources of noise in remote sensing systems. Many sources of noise are made up of so many events or characteristics of the system that they are impossible to identify or model, either deterministically or stochastically. What this taxonomy is meant to do is to identify major categories of noise components as locations of models or descriptions of components as they become understood.

Figure 1 shows the noise taxonomy as presently developed. Noise effects in each subsystem are grouped according to related sources. The following paragraphs will summarize the listed noise factors in each category and explain some of the terminology used.

In considering the scene, noise is seen to occur due to surface effects, goniometric effects, and atmospheric effects. Surface effects are due to the many variations that occur on the ground or surface of the Earth because of physical characteristics of the scene. Within class variation (also referred to as 'scene noise') is included because it manifests itself as a degrading factor in many classification schemes, although the spectral variation of a particular cover type may indeed provide the clues to its identification and thus can be considered a 'signal'. Background variations are the reflectance associated with components of the scene that are not the primary interest. Mixed pixels are a result of sensor resolution and of the macroscopic size of scene components, and in fact, for all practical systems, every pixel is 'mixed' to some degree. Adjacent reflections refer to radiance detected by the sensor as part of the scene but which is actually due to surface components outside the sensor's instantaneous field of view (IFOV). Surface slope, aspect, and obscuring objects are mostly of relevance in mountainous terrain where severe distortion of land cover reflectance can occur.

Goniometric and atmospheric effects also degrade the scene. Goniometric (angle related) noise factors include effects due to the macroscopic angles between the illumination, the surface, and the sensor. Also included in this category are the polarization and

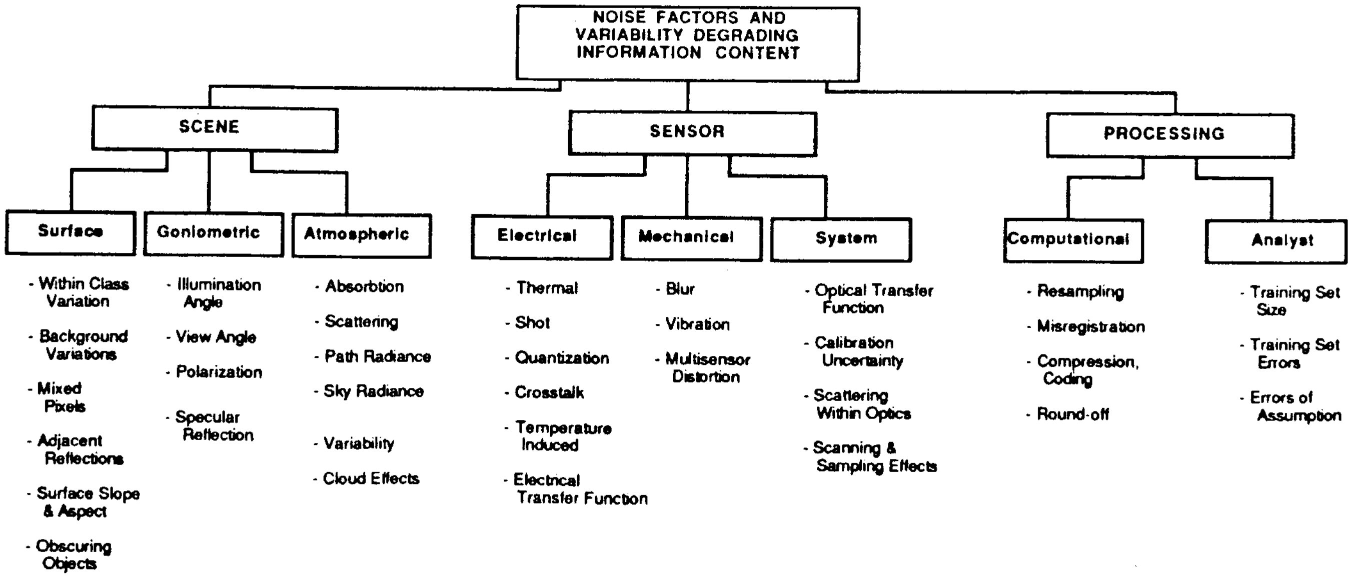

Figure 1. Noise and information degrading effects in a remote sensing system.

specular reflection effects which result when light reflects off of the surface of a target without entering. (See Vanderbilt, et al,1985). Atmospheric effects include the absorption and scattering that reduce both incident irradiance and exitance of a surface patch. Correspondingly, these quantities are increased by energy scattered in to the sensor by path radiance, and onto the surface by diffused sunlight referred to as sky radiance. All of these effects are subject to severe variability in both temporal and spatial domains.

In the sensor, the process of converting the incident electromagnetic energy into a discretized representation of the scene has many possible sources of error, or noise. Considering electrical effects, thermal, shot, and 1/f noise can occur in the detector or in any of the electrical amplifiers in the sensor. Error is introduced by the analog to digital conversion and is called quantization noise. Sensor response is affected by the overall electrical transfer function due to limited detector response, analog filters, and bandpass characteristics of analog amplifiers in the sensor. Crosstalk between cables in the sensor feeding the power circuits or communication circuits has been observed to induce false variations in the signals corresponding to the scene image (see Wrigley, et al, 1984). Also, variations in detector response due to changes in the ambient temperature can alter the sensor response.

Degradation of the image can be caused by mechanical effects such as vibrations aboard the sensor, or by the movement of the sensor during the finite detector response time leading to a blurring of the image. Also included in this category are the effects due to mechanical misalignment of sensors in multispectral sensors looking at the same spot on Earth.

Other sources of information degradation by the sensor are included in the system category. The optical transfer function is the optical analog of the electrical transfer function and includes the effects of finite apertures and defines the resolution of the sensor in terms of a spatial and spectral frequency response. Also within the optics, scattering may occur due to particles or aberrations. Electrical scanning and sampling in the spatial domain introduce distortions in the scene that must be considered. Calibration uncertainty is a 'catch-all' phrase that refers to the initial and subsequent degradation of the overall sensor response according to some calibration standard.

Errors and degradations are also introduced in the processing used to extract the desired information from the scene. Resampling used to register multiple data sets or correct geometrical distortions can often itself introduce errors in the image. Errors can also be made in the registration process. An error that will become more important as data sets grow exponentially in size will be errors introduced by coding and compression for transmission or storage of data. Another source of degradations are those introduced by the human analyst. These can include the effects of limited training set sizes or even errors in the training set data. Analysts can also be guilty of many errors of assumption including the multivariate Gaussian assumption for multispectral data, independence of pixels, stationarity (same spectral characteristics over spatial and temporal domains), training data accuracy and even in their interpretation of results.

NOISE MODELS

In the following paragraphs, we will mention some specific studies and models of 'noise' and even some 'signals' that follow along our taxonomy. These studies are but a sampling, but are included to give a brief overview and provide the interested reader with references.

In noise considerations, the most commonly thought of noise effect is degradation of the radiometric quantities measured by the sensor. Slater (1985) provides an excellent discussion of radiometric concerns and provides references for further research. Also Chapters 7 and 8 of Colwell (1983) contain many details about this type of noise in remote sensing.

One of the first models for vegetative canopies was developed by Suits (1972) and included effects for varying solar and view angles, and was later extended to include azimuth variations. A more general model for complex scenes including 3-D structure was presented by Kimes and Kirchner (1982). Angle effects were considered by Daughtry and Ranson (1986) in their study of modeling vegetative canopies. A very comprehensive computer model for the atmosphere is available in the LOWTRAN series, Kneizys, et al (1983). These types of models are based on radiative transfer methods and are useful in simulating a known type of scene.

Scene models based on stochastic representations are seen to be useful in classifying or simulating a general type of scene without knowing details. Nagata (1981) represents the image intensity of the scene with an autoregressive process model whose coefficients were calculated to provide an 'optimal' fit to the actual scene image. Turner (1983) predicts atmospheric effects based on typical variability at various locations rather than a specific effect based on local conditions.

The sources of noise in optical detectors have been heavily studied. The *Manual of Remote Sensing* (Colwell, 1983) and the text by Hudson (1969) are excellent sources of information. Landgrebe and Malaret (1986) give random process models for shot, thermal and quantization noise. 1/f noise is covered in a review paper by Keshner (1982), but its effects on remote sensing systems have not been studied directly.

Most studies on mechanical effects are of operational systems, such as in Wrigley, et al (1984), which considers multiple sensor registration. As imaging arrays of thousands of elements become available, sensor dropout or misalignment will become an important effect to consider in image analysis.

In the system category the optical effects due to the optical transfer function and scattering are covered also in the *Manual of Remote Sensing* (Colwell, 1983), and in a paper by Norwood (1974). These effects have also been studied from an empirical point of view by Anuta, et al (1984). Park and Schowengerdt (1982) studied the effects of sampling and reconstruction on the degradation of radiometric accuracy of remote sensing images and presented a general model for the degradation.

Considering noise in processing, the effects of sampling and interpolation for registration of images are presented in Schowengerdt, et al (1984) with an eye toward radiometric accuracy. Compression was studied by Ready, et al (1971), also with radiometric accuracy as a criterion. Misregistration and edge effects on classification are considered in Billingsley (1982) with models and expected performance for various parameters presented. Labovitz (1986) noted the effect of training sample separation in performing supervised classifications. Kalayeh, et al, (1983) investigated the quality of parameter estimation for various limited training set sizes.

NOISE AND SYSTEMS STUDIES

One of the first studies of noise in multispectral remote sensing systems was Ready, et al (1971). Twelve channel aircraft data obtained over agricultural land was classified several times, each with an increasing level of white noise added. A main result of this study was that the effect of noise on classification accuracy depended upon the variability of the surface cover.

Another study that came up with similar conclusions as part of its results was by Markham and Townshend (1981). This study primarily looked at the effects of spatial resolution of aircraft multispectral scanner data on classification accuracy. In general, they found a plateau of accuracy occurring at 30 meter resolution with further improvements in resolution bringing little increase in classification accuracy for large fields. But, they also found, similar to Ready, et al, that the inherent variability of a cover type affected classification accuracy in a complex manner that could not be predicted.

Landgrebe, et al (1977), in an empirical study, also found that increasing IFOV led to better classifier performance, as did increasing the number of spectral bands (if chosen properly.) Increasing additive noise decreased classification accuracy; however, the decrease was greater for a per pixel classifier than for a spectral-spatial classifier.

A simulation study by Huck, et al (1984) considered the entire remote sensing system with a computational model in order to evaluate the effects of design choices on classifier performance. Using stochastic models for the surface reflectance and sensor noise, and deterministic ones for the effect of the atmosphere, and sensor response, combinations of these were evaluated. One of the results showing interdependence of effects was that classifier performance was more severely affected at higher additive noise levels when the data was obtained under poor imaging conditions, than when obtained under good imaging conditions.

Finally, as a precursor to this current research, a study was done by Landgrebe and Malaret (1986) in analyzing the independent and interrelated effects of what are thought to be the three major sources of noise in remote sensing systems: 1) atmospheric effects, 2) sensor electrical noise, and 3) quantization noise. Stochastic models were used for the surface, sensor noise, and quantization noise, while a deterministic linear model was used for the atmosphere. One of the major results was that the degradation introduced by the atmosphere did not affect classifier performance when no other sources of noise were present, but did in fact increase the effect of other noise sources when they were present.

In summary, taken together these studies reinforce many heuristic expectations of the effects of noise, but also point out the complex nature of the sources of these effects. It is seen that the spectral inhomogeneity of most surface targets affect the amount of influence other elements of the system have on performance. Also, increases in the number of bands seem to help classification accuracy while increases in spatial and radiometric resolution approach limits of usefulness. These conclusions are but steps in the understanding of noise in the system, and indeed other interactions among components of the system may exist but have yet to be directly observed.

WHAT DIRECTION NOW?

How can we improve our understanding of the effects of noise starting from what has been noted? More comprehensive studies along with new measures of performance are a good place to start. Space sensors with fine spectral resolution are just around the corner and the expected enhancement for system operation is not fully understood. Accurate calibration and radiometric fidelity will also have an impact on the accuracy of information obtained. So as the technology develops to more accurately and completely extract data about the Earth, the degrading effects will become more important, and without their understanding, systems may be designed whose effects due to improved technology will only be overwhelmed by noise.

Hand in hand with understanding the noise in the system is understanding what information is desired from it. Classification is often the desired result, but to what level? Species identification, disease detection, expected yield in crops? What about biomass, or other complex measures of Earth processes? These types of measures and what constituent forces contribute to their computation is under ongoing research, but by providing a structure to the system analysis, we can begin to understand some of these complex interactions.

SUMMARY

Noise in optical remote sensing systems has been considered and defined as any information degrading variations that may occur in all aspects of the system. A taxonomy has been presented that provides a structure for considering the effects of noise. Several studies of the effects of noise from differing points of view have been presented to show current understanding of noise. It has been pointed out that the interrelated effects of noise sources on the output information of the system is not entirely understood, thereby preventing optimum systems to be designed for future missions or experiments.

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