Full spectral imaging: a revisited approach to remote sensing

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ABSTRACT

Current optical remote sensing instrument technology allows the acquisition and digitization of all of the reflected energy (light) across the full spectral range of interest. The current method for acquiring, transmitting, and processing this data is still based on the "multi-band" approach that has been used for the past thirty years. This approach was required due to limitations imposed by early instrument technology.

This paper will present generalized concepts for acquiring, pre-processing, transmitting, and extracting information from full-spectral, remotely sensed data. The goal of the paper is to propose methods for changing from the current "bytes-per-band" approach to the "spectral curve" approach. The paper will describe how the Full Spectral Imaging (FSI) approach has the potential to greatly simplify instrument characterization and calibration and to significantly reduce data transmission and storage requirements. I will suggest how these improvements may be accomplished with no loss of remotely sensed information.

Keywords: Remote sensing, hyperspectral imaging, data processing, data compression, information theory, calibration, characterization

1. INTRODUCTION

Full Spectral Imaging (FSI) seeks to provide remote sensing researchers the kind of information that they would have wanted when space borne remote sensing was invented, but that they could not have as the technology was not good enough. FSI is not "hyperspectral", "superspectral', or "ultraspectral" imaging. It is an end-to-end system for doing remote sensing. It involves everything from the technology of the observing instruments to the processes for producing the data products. Even though FSI includes the word ***spectral***, it includes all aspects of instrument technology.

Though many ideas will be mentioned in this paper, the key concept of Full Spectral Imaging is that it transmits all of the ***information*** (as described by Claude Shannon[1] and elaborated by others [2, 3]) acquired by the instrument rather than all of the ***data*** acquired by a traditional instrument. The quality of the ***information*** acquired is determined by the instrument performance characteristics which, presumably, have been determined by the science requirements. On the other hand, the ***data*** acquired by a traditional instrument includes signal, noise, redundant, and occasionally, useless bits. If the instrument characteristics really are determined by the science requirements, then the quality of the raw data will be sufficient to remove current objections to not having all of the raw data transmitted to the ground.

NOTE: This paper applies specifically to optical remote sensing instruments. In particular, it applies to the class of hyperspectral type imagers based on a dispersive element and a pushbroom image acquisition system. This could include all high spectral and spatial resolution Earth imaging systems, scientific and commercial.

1.1 History

In the beginning, remote sensing from space did not have the technological capability to collect continuous spectra. Terrestrial applications measure spectra continuously, typically using scanning monochromators. As space borne instruments could not be built with the capability to acquire continuous spectra and still cover large spatial regions with reasonable spatial resolution, another approach to remotely sensed data acquisition was required. After careful study, several spectral bands were selected to provide a representation of the continuous spectrum. For the past thirty years or so, variations of this multi-band approach have been used. A good summary of the situation, and an alternative approach, has been proposed by Landgrebe [4].

Current technology allows the acquisition of continuous spectra as all of the light across the reflectance spectrum may be collected, processed, and stored. This light is normally divided into bands as determined by instrumental

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(sensor) characteristics. Remote sensing researchers typically group these instrumental bands into the more or less standard bands that are used with traditional applications. Some applications, generally referred to as "hyperspectral" [5, 6], have been developed to use all of the instrument's bands. Still, these applications are based on the multiple band principles.

As a hyperspectral instrument may collect all of the light across the reflectance spectrum, the multiple bands form a continuous representation of the spectrum with a spectral resolution equal to the width of each band. A curve may be fitted to these multiple bands, as discussed in section 2.4. The result is a full spectral curve. This curve may be represented in many ways, most of which require far fewer bytes of data than the raw multiple band data. Conversion of the data from multiple bands to curves does not result in the loss of any information. Many techniques are available for conversion of spectral bands to spectral curves. This is a very complicated topic and will not be discussed in detail in this paper.

2. FSI METHODOLOGY

2.1 The problem

The basic problem of optical remote sensing is that the researcher wants spectral reflectance at the target but can only get spectral radiance at the sensor. It is a relatively straightforward process to measure spectral reflectance on the ground, the primary complicating factors being polarization and directional reflectance. A comparison of spectral curves acquired at the ground (left axis) and at the top of the atmosphere (right axis) is shown in Figure 1. In orbit, the signal at the sensor contains light reflected and scattered by the atmosphere in addition to the light reflected from the surface of the Earth. This problem becomes greater as the wavelengths become shorter. The signal at the sensor is also missing light absorbed by constituents of the atmosphere. This problem exists primarily at the longer wavelengths. It is therefore necessary to model the process of transmission of light through the atmosphere in order to "retrieve" the spectral reflectance. The modeling process requires an accurate measurement of spectral radiance at the sensor.

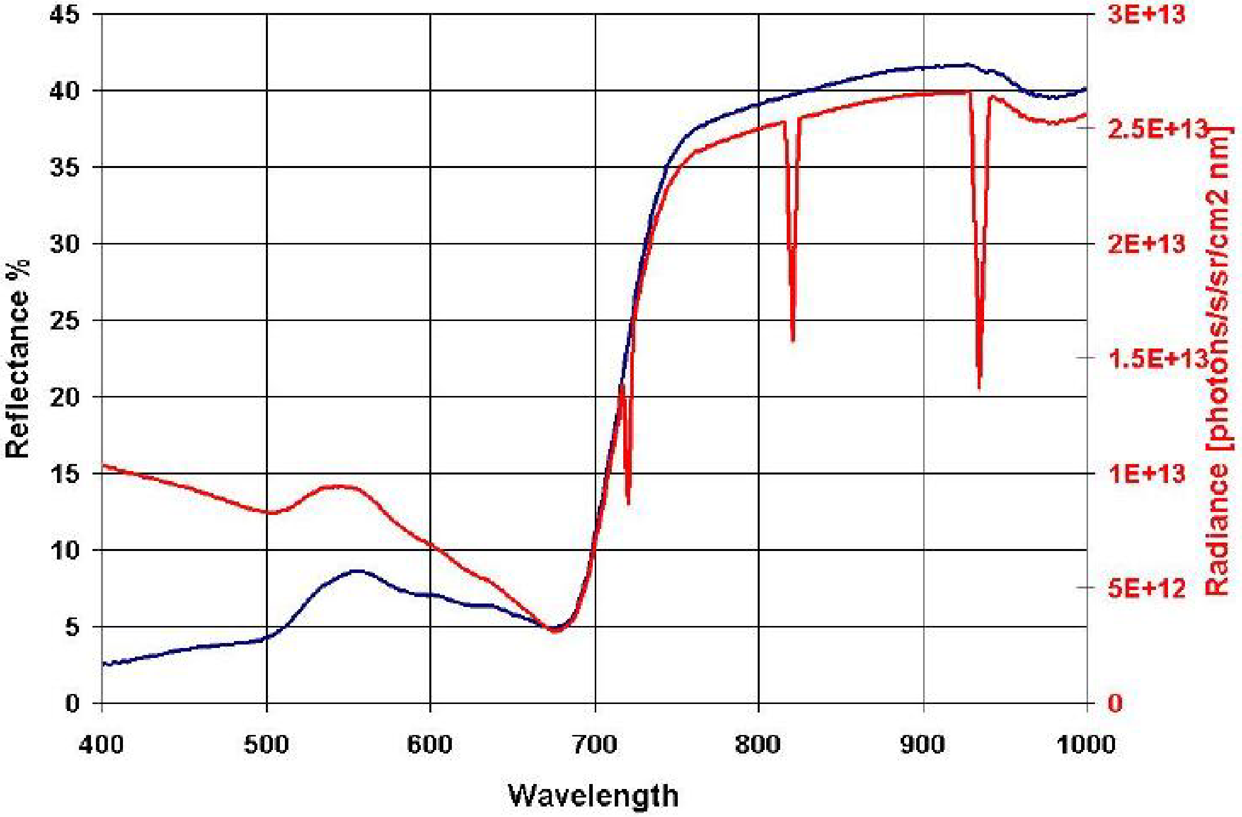

Figure 1: Typical vegetative spectral reflectance on the ground and spectral radiance at the sensor

2.2 The analogy

I decided to address this problem by revisiting the basic principles of spectral reflectance measurement. Spectral reflectance measurements are made in the laboratory by comparing the light reflected by a sample to the light reflected by a "perfect" reflector, making some basic assumptions about the linearity and baseline of the reflectometer. The result of this measurement is a continuous spectral curve of reflectance vs. wavelength. As the target is in very close proximity to the sensor, there is no need to correct for atmospheric effects, and the measurement may be made directly. By analogy, spectral reflectance measurements could be made directly by an instrument in earth orbit. To complete the laboratory measurement analogy, time invariant or "pseudo-invariant" targets [7, 8, 9] and vicarious calibration methods [10, 11, 12] must used. These techniques have been used in many remote sensing applications. As mentioned above, one must still be concerned about polarization and directional reflectance issues, as well as the problem of impure or "mixed" pixels that result from reduced spatial resolution at orbital altitudes.

2.3 The critical factors

While invariant targets can be very useful, an extensive selection of ground truth, or vicarious calibration sites, will be needed. Many sites are already established and maintained [13, 14, 15]. As the concept of FSI develops and is adopted by airborne and commercial remote sensing instruments, I expect that many more sites will be established. The statistical validity of vicarious calibration can be greatly enhanced using FSI, as a very large number of targets and spectral signatures are available. It is important to keep in mind that it is necessary to make simultaneous, or near simultaneous measurements of the ground truth sites from space and on the ground (or by airborne instruments). Historical or catalogued spectral signatures are of limited use, particularly for vegetation. The critical factor, however, is the acquisition of full spectral information. The spectral reflectance information is contained in the shape and features of the spectral curve, not in the absolute radiances. It follows logically that the more features you have the more information you will have. This implies that maximizing the spectral resolution and coverage, up to the point where no more features are available, is desirable.

2.4 Spectral bands to spectral curves

The typical hyperspectral imaging instrument produces many contiguous spectral bands. Because of the tradition of band usage, researchers generally treat hyperspectral data as multispectral data with lots of bands. This practice is both counterproductive, and a waste of "bandwidth". Many techniques are available to fit a curve to the multiple bands. Figures 2 and 3 illustrate the same dataset represented as multiple bands, and as a spectral curve. A thorough study is required to review curve fitting techniques, and to compare curve fitting to simply compressing the multi-band data. Some techniques may be specially tailored to accurately fit remotely sensed data while creating a minimal set of data. While many remote sensing scientists are skeptical of compression techniques that "pre-process" the data, these should be investigated as well [16]. The number of bytes needed to represent the spectral curve will be proportional to the information in the features of the curve. As mentioned above, details of curve fitting techniques are complex and will not be discussed in this paper.

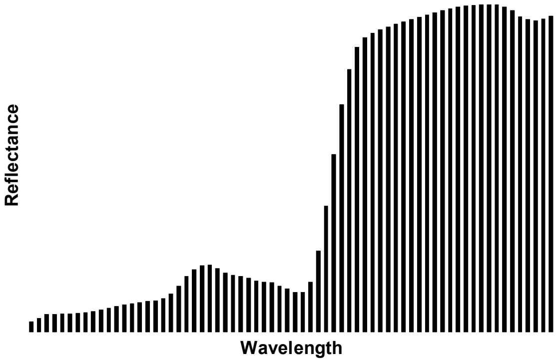

Figure 2: Hyperspectral multi-band data

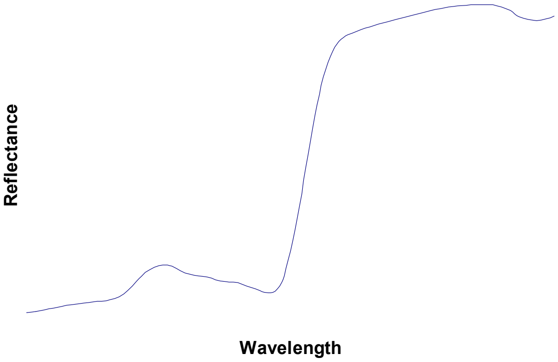

Figure 3: Spectral curve data

2.5 Pixels to images

Just as spectral curves may replace multiple bands, images may replace individual pixels or lines of pixels. Well known data compression and image storage technologies can greatly reduce the number of bytes required to store an image. Development of software and hardware using wavelet compression techniques, the JPEG 2000 standard for example, is well advanced. While the FSI images will consist of arrays of spectral curves, rather than multiple bands, the same image storage algorithms apply. The key to any data volume reduction concept is to treat that data in large scenes rather than one pixel or one line at a time. This approach will automatically deal with relatively featureless areas in scenes such as clouds, extensive agricultural areas, and large bodies of water. The number of bytes needed to represent the scene will be proportional to the information content of the scene.

3. FULL SPECTRAL IMAGING SYSTEM FEATURES

3.1 Introduction

As mentioned above, FSI is an end-to-end approach to remote sensing instrument technology. To optimize performance, all features of the system must be considered to eliminate any problem areas or “bottlenecks”. The key to good instrument performance is simplicity and stability. With the exception of the detectors, all of the technology required for an FSI instrument is available “off-the-shelf”. The detector technology is also available, but the exact detector configurations would have to be custom built, a common process these days. Some of the features that would enhance the performance of an FSI instrument are mentioned here. Other features are being considered. Details of the FSI instrument design are the topics of separate investigations and will not be discussed in this paper.

3.2 Fore optics and imaging system

Moving parts always present a problem for space borne instruments. Scan mirrors, in particular, are troublesome. A FSI instrument should utilize “pushbroom” technology. Pushbroom technology has many advantages, the primary being that no moving parts are required. Other advantages of pushbroom technology are:

- seamless and continuous acquisition of the image
- wide field-of-view (FOV) all-reflective optical system (good throughput in the UV and blue)
- constant optical system configuration (no angle changes)
- option to map the curved Earth surface onto the flat detector plane (optical “bow tie” distortion correction)

3.3 Multiple focal planes

Instrument throughput, spatial coverage, and spectral response can be enhanced using multiple focal planes. The wide FOV imaging system mentioned above could easily accommodate multiple entrance slits. Parallel slits would be used to enhance the spectral coverage, and serial slits would be used to expand spatial coverage. These multiple slits would be optically connected to several spectrometer and detector combinations. Each spectrometer would have identical optical elements except for the dispersion characteristics of the grating and the detector. This would assure accurate co-registration of all the focal planes, after taking into account the slight temporal/spatial displacements of the entrance slits. Optically, the multiple focal planes could be an advantage if it is necessary to curve the focal plane. Each focal plane would have its own signal processing chain which would decrease the demand on the electronic subsystems. Multiple focal planes represent a modular approach to instrument construction. More or less focal planes may be used depending on the scientific requirements. Figure 4 illustrates a possible configuration of the multiple focal planes' entrance apertures.

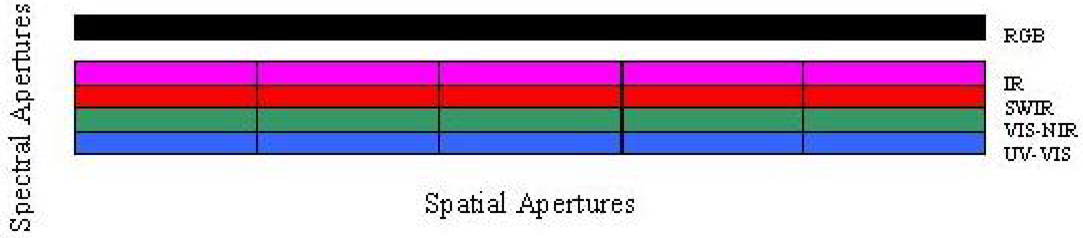

Figure 4: Multiple slit focal plane configuration

3.4 Detector readout

Current detector technologies provide for a variety of "smart" readout methods. For CCD detectors, one of the simplest smart readout methods is "on-chip binning". On-chip binning can be used when signal levels in adjacent pixels are virtually the same. On-chip binning is particularly useful when signal levels are low as it sums the signals and eliminates the noise attributable to multiple readouts. The disadvantage of on-chip binning is that the bins must be selected before the detector is read out. There is no possibility to make "on-the-fly" changes to optimize the detector output for different spectra.

Alternative detectors, CMOS for example, allow "non-destructive" readout. This provides for the possibility to evaluate the spectral curve before reading it out. An optimal implementation of FSI will require a thorough study of detector technologies and on-board computational capabilities. Advances in detector technology will enable enhanced on-chip readout capabilities, including some of the features discussed in the next section.

3.5 Non-linear analog to digital (A/D) conversion

One of the most important performance measurements, if not the most important, for a remote sensing instrument is signal-to-noise-ratio (SNR). FSI technology allows several techniques to be used to enhance the SNR, usually at the expense of spectral and/or spatial resolution. One lingering problem is the difficulty in obtaining adequate SNR at the blue end of the spectrum. For water and ocean researchers, who need good SNR in the blue and have targets with low reflectance, this is a serious issue. This problem is caused by several factors, all conspiring together. These are poor transmission by glass optical elements, low efficiency of dispersive systems in the blue, and poor blue response in detectors. The use of an all-reflective, as mentioned above, helps to alleviate the first problem. By the choice of dispersing element, a FSI system can be optimized for blue response, at the cost of longer wave response. Detectors with enhanced response in the UV and blue may be used.

Even with optical enhancements, the signal, or number of "counts" that water researchers have available after atmospheric effects are taken into account, may not be suitable. The low count level problem is the primary reason that water researchers object to data compression, or to any kind of pre-processing of their data. One way to get more counts representing small signals is to use non-linear A/D conversion. The non-linearity of choice is the square root, as illustrated in Table 1 below. Square root A/D conversion provides reasonable numbers of "counts" at the low end of the range, and does not sacrifice resolution at the high end. Linear conversion has problems at the low end, and typical base-10 logarithmic conversion has problems at the high end. The square root A/D conversion would have to be a two-step process. The first would be an analog square root compression at the detector or detector amplifier level. The second would be a traditional A/D conversion. Square root conversion will also be advantageous as it will speed the A/D process because fewer bits will have to be digitized.

Input	12-bit	16-bit	12-bit	10-bit	12-bit	10-bit	8-bit
	Linear	Linear	Log	Log	Sqrt	Sqrt	Sqrt
1	0	0	0	0	4	1	0
2	0	0	206	51	6	1	0
3	0	0	326	81	7	2	0
6	0	0	531	133	10	3	1
10	0	1	683	171	13	3	1
20	0	1	888	222	18	5	1
30	0	2	1008	252	22	6	1
60	0	4	1214	303	32	8	2
100	0	7	1365	341	41	10	3
200	1	13	1571	393	58	14	4
300	1	20	1691	423	71	18	4
600	2	39	1897	474	100	25	6

(continued on next page)

Input	12-bit	16-bit	12-bit	10-bit	12-bit	10-bit	8-bit
	Linear	Linear	Log	Log	Sqrt	Sqrt	Sqrt
1000	4	66	2048	512	130	32	8
2000	8	131	2254	563	183	46	11
3000	12	197	2374	593	224	56	14
6000	25	393	2579	645	317	79	20
10000	41	655	2731	683	410	102	26
20000	82	1311	2936	734	579	145	36
30000	123	1966	3056	764	709	177	44
60000	246	3932	3262	815	1003	251	63
100000	410	6554	3413	853	1295	324	81
200000	819	13107	3619	905	1832	458	114
300000	1229	19661	3739	935	2243	561	140
600000	2458	39322	3945	986	3173	793	198
1000000	4096	65536	4096	1024	4096	1024	256

Table 1: Comparison of Analog-to-digital Converters (A/D full scale count = 1.00^6)

3.6 Calibration

As discussed in section 2.2 above, the FSI system would have no need of on-board calibration systems. As most calibration systems involve some sort of moving or active parts, this would improve system reliability. All calibration would be done vicariously. Calibration would be done empirically rather than via models. One of the primary attributes of the proposed FSI instrument is its simplicity. In addition to having no optical scan system, the FSI instrument would have no deployable solar reflectors, no calibration lamps, and no flip mirrors. Elimination of these disturbing mechanical systems contributes to response stability and decreases the need for frequent instrument calibration. After a thorough characterization of the FSI instrument before launch, the response stability can be verified using ground truth.

3.7 Instrument characterization

The FSI instrument, like the hyperspectral instrument, is much easier to characterize than the multispectral instrument. The fact that the instrument captures all of the light across the spectrum means that spectral response may be characterized in one “pass”. For a multi-spectral instrument, each band must be characterized individually. Characteristics such as stray light, out-of-band rejection, pixel spill-over, etc., can be characterized using well known methods.

The imaging characteristics of the FSI instrument can also be characterized using well known methods. Current designs for hyperspectral instruments virtually eliminate some of the classical problems such as “smile” and “keystone” effects. The Earth curvature (“bow tie” distortion) correction would require some innovative optical design of the fore-optics but is well within the realm of current optical design and fabrication technology.

3.8 Data Compression

The techniques for conversion of spectral bands to spectral curves and for conversions of pixels to images discussed in sections 2.4 and 2.5 above may provide all the data compression that is needed in a FSI system. Further study and development will be needed to create the algorithms and to design the hardware needed to convert from bands to curves, and to compress scene images. Alternative data compression techniques [17] and techniques to simply compress the three-dimensional “hyperspectral hypercube” will also be considered [18, 19]. This concept, which may be referred to as “Spectro-Spatial compression” or SSC offers the possibility to make the automatic trade between spectral and spatial resolution. Capabilities for on-board computation are critical and will also have to be taken into account. Signals from the multiple focal planes will have to be combined to utilize SSC most effectively. Fortunately, extremely high speed data and image processing hardware is already available, and is being constantly developed. Work that has been done for applications other than remote sensing will be most useful in this area.

It should be noted that, for those who insist on using top of the atmosphere radiances and applying their own retrieval algorithms, the information in that format may be extracted from the FSI data. The FSI process results in no loss of remotely sensed information.

3.9 Data transmission

While typical multi- and hyperspectral systems have constant data transmission rates, the FSI system will not. The data rate will depend on the amount of information in the data. For example, the data rate for cloudy scenes will be much less than that for the same scene without clouds. Both the spectral and spatial information content in a cloudy scene is much less than in a clear scene. The difference between the number of bytes required to represent a relatively clear scene and a cloudy scene using simple JPEG compression for both scenes is illustrated in Figures 6 and 7.

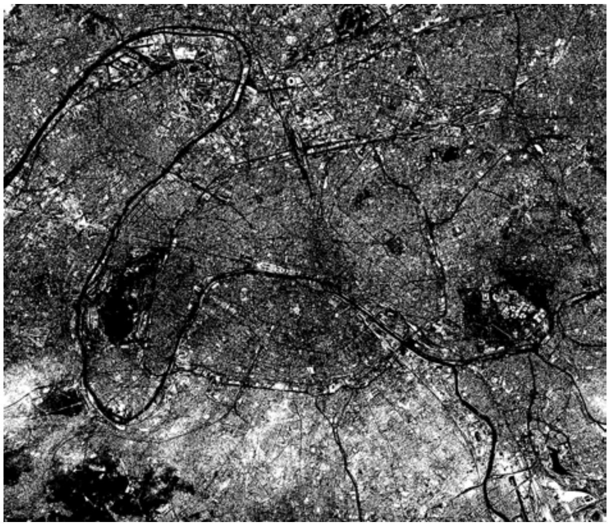

Figure 6: Scene with few clouds (7.5 Mbytes)

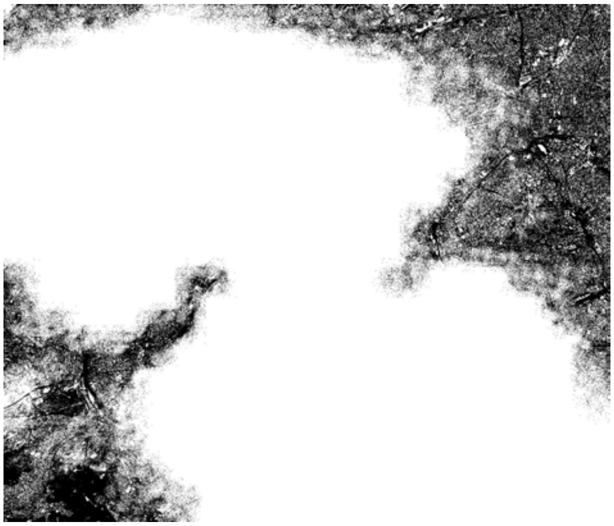

Figure 7: Scene with thick clouds (0.85 Mbytes)

Once the data has been properly compressed and formatted, it is expected that normal buffering and transmission methods will be adequate. A direct downlink to provide near real-time data to users should be a high priority in an FSI instrument.

3.10 Auxiliary imaging (AI) systems

Many remote sensing systems have the capability to acquire high spatial resolution panchromatic (“pan”) images. The pan images acquired are often referred to as the “sharpening band”. This capability could be easily incorporated into an FSI system. One of the multiple focal planes could contain a linear array, the typical device used for producing pan images. Instead of using the typical monochrome, single linear array, it would be advantageous to use a “tri-color” or RGB (Red – Green – Blue) array. This would be of much greater use than the traditional sharpening band. The same data reduction techniques that are applied to the main FSI system would also be applied to scenes in the AI system.

4. ESTIMATED FSI INSTRUMENT PERFORMANCE SPECIFICATIONS

NOTE: Details of the FSI instrument configuration will not be discussed in this paper. Some of the features were discussed in the previous section. The means for implementation of these features will be the subject of lengthy studies. Some details are discussed in a previous work [20] which, at that time proposed technologies that were somewhat beyond the state-of-the-art, will have to be revised if the development of FSI is to continue. It may be noted that the specifications for a typical FSI instrument have much in common with current LANDSAT and SPOT instruments. Employment of the principles of FSI can apply to commercial sensors just as well as to scientific sensors.

4.1 Assumed operational parameters

Parameter	Value
Altitude	705-822 km
Swath width	~ 200 km
Orbit	Sun synchronous

4.2 Performance specifications

Parameter	Value	Note
FSI spectral range	0.34 – 2.4 microns	4 spectrometers
FSI spectral resolution	5 – 20 nm	Spectral range dependent
FSI spatial resolution	10 – 30 meters	Spectral range dependent
FSI dynamic range	10^6	Square root conversion
FSI SNR	200:1 – 1000:1	Spectral range dependent
AI spatial resolution	1 - 2 meters	Red – Green – Blue (RGB)

5. CONCLUSIONS

This paper has presented some new approaches and ideas for remote sensing. The paper is meant to stimulate discussion of new and alternative methods for remote sensing. The FSI system concept offers researchers the type and quality of information that they would have liked to have when they first started Earth observations from space. While adoption of FSI would cause some initial upheaval in the remote sensing community, in the long run it would significantly simplify many aspects of remote sensing. This simplification would extend from remote sensing instrument technology to data storage, processing, and interpretation. Widespread adoption of FSI by ground, airborne, and space-borne instruments would simplify the distribution and combination (data fusion) of data as the spectral curve format would be more general than the current multi-band formats.

The technological capability to implement FSI is currently available. Technology is not the problem. Acceptance of FSI and all that it implies by the remote sensing community is the problem. Most of the background material and the majority of the support for FSI has come from outside the traditional remote sensing community, particularly from those specializing in information theory (in particular Reichenbach, et. al. [21, 22, 23]) and image processing. Significant developments have been achieved by the defense communities. Much of the technology has been developed for applications other than remote sensing. The author has only begun to explore the resources available to fully develop the principles of FSI. This paper is only a starting point. It will raise more questions than it answers. Many topics are waiting to be explored.

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