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Title:

MULTI-SPECTRAL BAND SELECTION FOR SATELLITE BASED SYSTEMS

Author(s):

William B. Clodius, NIS-2
Paul G. Weber, NIS-2
Christoph C. Borel, NIS-2
Barham W. Smith, NIS-2

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Multi-spectral band selection for satellite-based systems

William B. Clodius, Paul G. Weber, Christoph C. Borel, and Barham W. Smith

Los Alamos National Laboratory, MS C323, Los Alamos, NM 87545

ABSTRACT

The design of satellite based multispectral imaging systems requires the consideration of a number of tradeoffs between cost and performance. The authors have recently been involved in the design and evaluation of a satellite based multispectral sensor operating from the visible through the long wavelength IR. The criteria that led to some of the proposed designs and the modeling used to evaluate and fine tune the designs will both be discussed. These criteria emphasized the use of bands for surface temperature retrieval and the correction of atmospheric effects. The impact of cost estimate changes on the final design will also be discussed.

Keywords: multispectral, design, analysis, modeling, satellite

1. INTRODUCTION

The design of a multispectral imaging system in many ways is more an art than a science, with many tradeoffs for which there is no single objective criterion. This is particularly true for the selection and definition of the system's spectral bands. By definition, a multispectral system is limited in the number of spectral bands and the bands selected represent an explicit or implicit judgment that the bands not selected were not as valuable. The design decisions are liable to be more detailed in the case of a satellite based sensor, due to its longer lead-time, higher risks, and higher costs, than for some other sensor systems. The authors have recently been involved in the design and evaluation of such a satellite based multispectral system, the United States (US) Department of Energy (DOE) Multispectral Thermal Imager (MTI), and hope that this account of their analysis may be of interest to others.

While much of the following discussion is of general interest, the design of any sensor is biased by its applications so that some of the details of the MTI system design need not be of interest to other designs. In particular, MTI was intended to be a satellite based system for terrestrial observation with an emphasis on obtaining quantitative information on surface temperatures. Because it is to be satellite based, MTI's band selection had to consider the effects of stratospheric ozone and other atmospheric variables. The goal of quantitative analysis of surface temperatures placed a strong emphasis on information from the thermal infrared (IR) portion of the spectrum, on information about the intervening atmosphere, and on identification of surface materials.

The bands were only part of the system and had to be consistent with the overall system design. The initial design goal for MTI was for a minimal system that would fit on a small launch vehicle and a moderate sized field of view, 20 km at nadir. The field of view was subsequently reduced to about 12 km to save money by reducing the focal plane array and simplifying optical design and implementation. In order to minimize the size of the focal plane and hence simplify optical design and implementation, intermediate designs had only fourteen bands, but that was later relaxed to allow fifteen bands. Power constraints affected the band selection in the long wave infrared, Section 6. Other aspects of the overall design, for example F number, field of view, and the use of a single focal plane, effectively limited the minimum spectral width of the bands, either through signal to noise considerations, or through the difficulty of implementing consistent band filters for the range of angles of incidence. The use of a single focal plane, selected primarily because a beam splitter would complicate calibration, meant that the entire optical train had to be compatible with the imaging bands, which in turn limited the extremes of the spectral range covered, Section 2.3.

Further author information –

W.B.C.(correspondence): Email: wclodius@lanl.gov; Telephone: 505-665-9370; Fax: 505-667-3815

P.G.W.: Email: pweber@lanl.gov; Telephone: 505-667-5776; Fax: 505-665-4414

C.C.B.: Email: cborel@lanl.gov; Telephone: 5-667-8972; Fax: 505-667-3815

B.W.S.: Email: barham@lanl.gov; Telephone: 505-667-1585; Fax: 505-667-3815

Table 1. MTI spectral band characteristics

Band ID	Spectral Region	Wavelength range (μm)	Nominal GSD (m)	Detector material	Description
A	VIS	0.45-0.52	5	Si-PIN	Blue "True Color"
B	VIS	0.52-0.60	5	Si-PIN	Green "True Color"
C	VIS	0.62-0.68	5	Si-PIN	Red "True Color"
D	NIR	0.76-0.86	5	Si-PIN	Vegetation
E	NIR	0.86-0.89	20	InSb	Water Vapor
F	NIR	0.91-0.97	20	InSb	Water Vapor
G	NIR	0.99-1.04	20	InSb	Water Vapor
H	NIR	1.36-1.39	40 (20)	InSb	Cirrus
I	SWIR	1.54-1.75	20	InSb	Surface
J	MWIR	3.49-4.10	20	InSb	Surface
K	MWIR	4.85-5.05	20	InSb	Atmosphere
L	LWIR	8.01-8.39	20	HgCdTe	Atmosphere
M	LWIR	8.42-8.83	20	HgCdTe	Surface
N	LWIR	10.15-10.7	20	HgCdTe	Surface
O	SWIR	2.08-2.37	20	InSb	Surface

Although the thermal IR was of primary interest in the initial system design, and restricting the design to the thermal IR was sometimes proposed, the official design at all stages included bands in portions of the visible (VIS) 0.375-0.75 μm, near IR (NIR) 0.75-1.5 μm, short wave IR (SWIR) 1.5-3 μm, mid-wave IR (MWIR) 3-6 μm, and long wave IR (LWIR) 6-15 μm spectral ranges. This broad spectral coverage was driven not only by the desire for atmospheric information, but also by the beliefs that the higher spatial resolution possible at shorter wavelengths would prove useful, and that other missions would help to justify the costs of a satellite based system. This led to a variety of proposed bands many of which were eventually removed from the design as an extensive system modeling effort.[1] gave a better appreciation of their relative value and costs. The final set of spectral bands is summarized in Table 1 in terms of their identifier (ID), spectral range, approximate ground sample distance (GSD) for nadir looks, detector material, and a brief description. The wavelengths of each band are the 10% transmission levels relative to the peak transmission as specified by the design team. The band cutoffs as implemented are weakly dependent on focal plane location, differing from the specifications by a few percent of the bandwidth. Photodetectors were used instead of energy detectors to achieve acceptable response times.

As with many terrestrial multispectral sensor designs, much of the band selection process was driven by the transmission characteristics of the earth's atmosphere. The relationship of these bands to the atmospheric transmission bands is illustrated by Figure 1 which places rectangles indicating the band locations and widths above a typical atmospheric transmission curve for a nadir looking satellite,* as calculated using the Air Force Philips Lab Geophysics Directorate code, Modtran 3.5.[2] In general, bands on peaks in the atmospheric transmission curve are useful for obtaining surface information, and bands within valleys in the curve are useful for atmospheric characterization. Design decisions primarily involve deciding which peaks are of sufficient interest to deserve multiple bands, which peaks are of negligible interest, and how to best cover the valleys in the transmission curves.

The details of the selection and definition process for the above bands will be discussed below separated according to spectral range. A brief overview of the general characteristics of the spectral range will be given, followed first by a discussion of the selected spectral bands, and then by a discussion of alternative bands that were considered but not selected. Special emphasis will be placed on the bands that involved the most detailed design work, i.e., the NIR bands, particularly E, F, and G, the MWIR bands, particularly band K, and the LWIR bands, L, M, and N.

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* This and other Modtran plots are, unless otherwise noted, for the midlatitude summer model (3220 Atm-cm H_2O and 0.084 Atm-cm CO for a vertical column), with the ground surface at an altitude of 250 m, rural aerosols, an albedo of 0.1, sun at 45° zenith angle, surface at 293 K, and 360 ppm CO_2. Some examples have the same model except US Standard model H_2O (1550 Atm-cm H_2O for a vertical column), or enhanced CO in the first 7 km (0.116 Atm-cm CO for a vertical column).

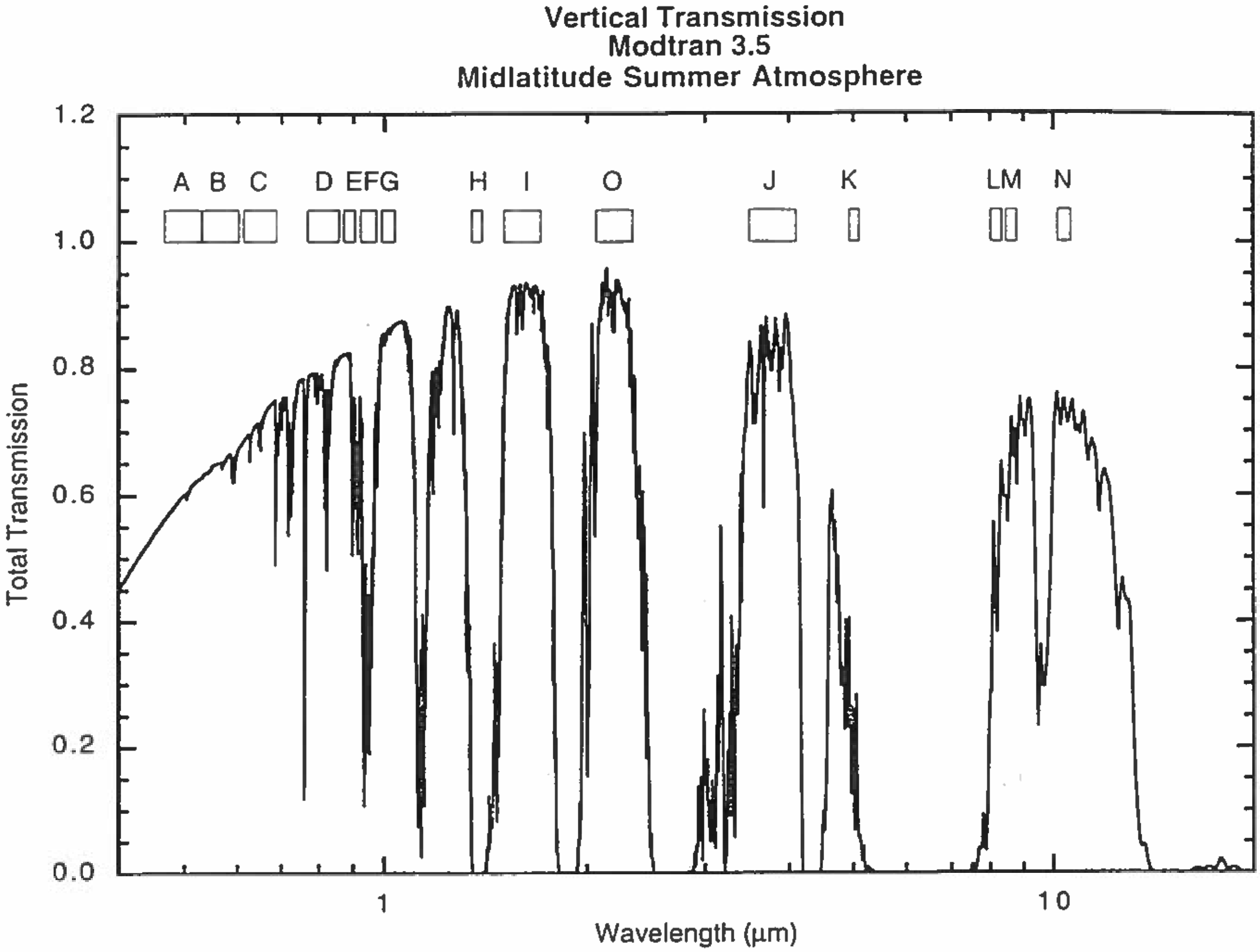

Figure 1. Comparison of MTI band definitions (rectangular boxes) with a typical atmospheric transmission.

2. VISIBLE BAND SELECTION

2.1 Overview of the visible (0.375-0.75 μm) spectral range

The visible spectrum is the most familiar spectral range to all seeing humans. The visible offers the best imaging resolution of the spectral ranges discussed here due to its short wavelengths, but limited pixel sizes, optical aberrations, photon shot noise, and atmospheric scattering limit achieved resolution. While most surface materials have a large degree of spectral correlation within this range, the green portion of the spectrum is of interest as an indicator of vegetation chlorophyll and this range can be useful for material identification. Further, most natural surface materials, snow is an obvious exception, have low albedos in the visible limiting radiance levels. As a consequence of the spectral correlation and low radiance, many multispectral sensors limit their spectral coverage in this range to one panchromatic band that extends into the NIR or three (red, green, and blue) bands.

The visible spectrum was of interest to MTI primarily because of its potential for high spatial resolution, material identification, and vegetation analysis. The visible spectrum was not considered to be of interest for atmospheric analyses as the atmosphere has little spectral structure in this region. Silicon diodes were the preferred MTI detectors in the visible because their mature technology yields inexpensive large arrays of high quantum efficiency, although silicon diode arrays are not normally designed to operate in a cryogenic environment, such as that of the MTI focal plane.

2.2 Selected visible bands

The visible bands, A (0.45-0.52 µm), B (0.52-0.60 µm), and C (0.62-0.68 µm) correspond closely to the Landsat Thematic Mapper visible bands,[3] although, because of minor variations in spectral response with focal plane position, an exact correspondence was not enforced in the design. They were selected to provide bands comparable to bands on other sensor systems, true color images, vegetation chlorophyll data via band B, ocean water quality analyses and high spatial resolution data for sub-pixel analyses. Because of their high spatial resolution, these bands were the main drivers of the telescope quality, onboard data storage and downlink requirements for the MTI system. Each of the Si-PIN bands has one quarter the GSD and about sixteen times the data storage of each of the InSb and HgCdTe bands. These ancillary requirements and the lack of a direct application to the main MTI mission made these bands controversial among the system design team and deleting some or all of them from the system requirements was debated several times although they remained among the official bands throughout the design process.

2.3 Alternative visible bands not selected

In addition to bands A, B, and C, two other bands in the visible spectral range were considered for implementation, a "violet" band usually defined as 0.42-0.46 µm to approximate the Coastal Zone Color Scanner short wavelength band,[4] and a panchromatic band covering the response range of the silicon detectors. The "violet" band was potentially useful for ocean water quality studies, but had a number of disadvantages that caused its rejection: first, it was difficult to find optical materials compatible both with the "violet" band and with the LWIR bands;[†] second, the solar spectral radiance and typical albedos were small in this band so it would be relatively noisy; finally, it has relatively poor atmospheric transmission. The panchromatic band was mostly considered as an alternative to bands A, B, C, and D, providing the high spatial information at a reduced storage and downlink cost, with, however, a loss of spectral information. The decision to retain the other bands made the panchromatic band unnecessary.

3. NEAR INFRARED BAND SELECTION

3.1 Overview of the NIR (0.75-1.5 µm) spectral range

The NIR spectral range offers good spatial resolution, often, in the 0.75-0.9 µm range, comparable to the visible due to its lower atmospheric scattering (reduced adjacency effect). Vegetation, unlike most other materials, has a high albedo in this range due to lignin giving images in this band large contrast, and, in combination with the visible bands, widespread application in vegetation characterization. This region also has several moderate to strongly absorbing water vapor bands that are useful for atmospheric characterization. This region was therefore of interest to MTI for atmospheric corrections, vegetation analyses, and material identification.

Silicon diodes are the detector of choice at the low end of this spectral range. The detector material of choice at the high end depends primarily how far into the infrared the same detector material would be used. The desire to use the same detector material over as wide a spectral range as possible and the need for cryogenic cooling for the LWIR bands made InSb the MTI detector of choice at the high end of this spectral range. Non-silicon detectors in multi-spectral systems tend to have significantly larger pixel sizes than silicon detectors, primarily because diffraction limits optical resolution at the longer wavelengths associated with the non-silicon detectors. The MTI NIR and SWIR InSb bands pixels are a factor of four larger than the Si-PIN pixels, rather than the more common factor of two, due to several design choices: the use of a power of two pixel size relationship between the InSb and silicon detectors to potentially simplify registration; the use of the same pixel size for all InSb bands to potentially reduce costs; and the need for relatively large pixel sizes to obtain good signal to noise in the low radiance MWIR bands.

3.2 Selected NIR bands

The NIR bands cover a variety of applications: vegetation health (D with B and I), columnar water vapor retrieval (E, F, and G), and thin cirrus detection (H). The definition of band D (0.76-0.86 µm), which is mostly intended for vegetation health, water body, and high spatial resolution analysis, was relatively straightforward and similar to the comparable Landsat band. Because it used the same detector materials as bands A, B, and C it had many of the same controversies, but because of its

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[†] The main optical material problem was with the window on the cryogenic chamber designed to prevent contamination of the foc plane. Two window materials were considered, one having good transmission from the blue to about 11.6 µm, the other having poor transmission in the blue, but good transmission beyond 11.6 µm. In the end other constraints were more important than this one. The redefinition of band N to less than 11µm for reasons of focal plane produceability and costs made both window materials acceptable.

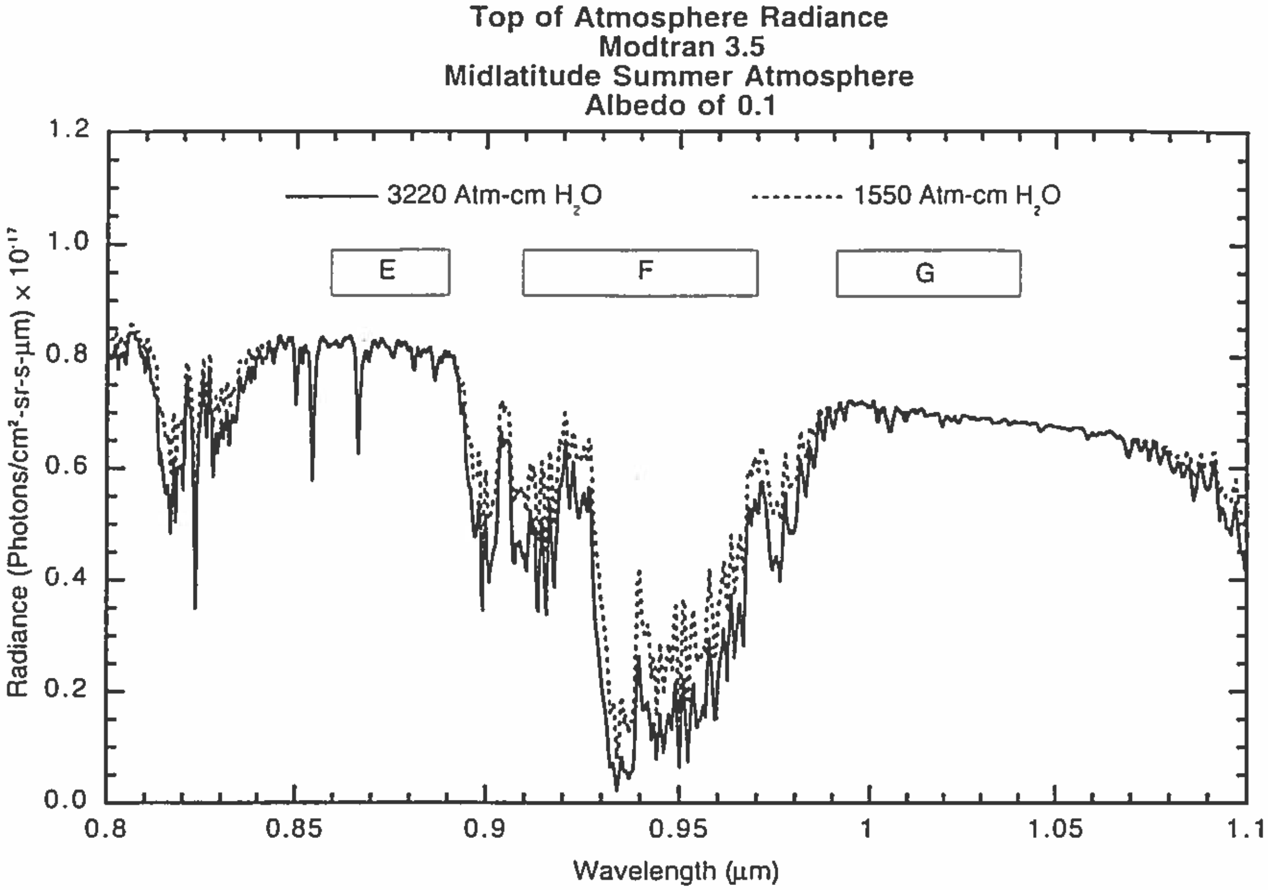

Figure 2. Comparison of E, F, and G band definitions (rectangular boxes) with a top of atmosphere radiance.

higher atmospheric transmission and direct applicability to vegetation health, was generally the least controversial of the four Si-PIN bands. The other four bands require more detailed discussion.

Bands E (0.86-0.89 µm), F (0.91-0.97 µm), and G (0.99-1.04 µm) are intended to retrieve columnar water.[5] Band F is centered on a water vapor absorption feature, while bands E and G are positioned on both sides of band F, but just outside the absorption feature. The responses of band E and G are to be interpolated to estimate the theoretical band F response in the absence of water vapor, and the ratio of the band F response to this ideal response is a useful indicator of integrated water vapor. For higher accuracy, the responses should be corrected for atmospheric scattering.[6]

The design of bands E–G entailed significant effort compared to many other bands. There are two atmospheric absorption bands, centered on 0.94 and 1.14 µm, useful for the above algorithm.[5] The 0.94 µm feature was selected for the implementation, primarily because absorption at 0.94 µm is weaker than at 1.14 µm so the 0.94 µm feature is more useful at larger water vapor concentrations. However, selecting the 0.94 µm band resulted in bands E–G covering the spectral range where the optimal detector material transitions from silicon to InSb. This caused the largest concern for band E and three alternative designs were considered: first, implementing band E using Si-PIN diodes; second, dropping band E entirely and using band D in its place; and, third, using a narrow/wide approach similar to that of Frouin *et al.*[7]. However, average albedos in D are not as well correlated with albedos in F and G as are albedos in E, implementing E using Si-PIN diodes would have unnecessarily increased storage and bandwidth, or introduced a new detector design, and the narrow/wide approach is less accurate. Finally, band E and G are relatively narrow, so their detailed spectral response varies with position on the focal plane. The design attempted to minimize effects from this variability by placing these bands on extremas in the top of atmosphere radiances for surfaces with flat albedos, which partially compensates for spectral variations in the solar spectrum and atmospheric scattering and absorption. This positioning is illustrated by Figure 2.

Band H (1.36-1.39 µm) is intended for the detection of sub-visual cirrus. It is centered on a strong water vapor absorption feature, at 1.37 µm, and, except under unusual circumstances, radiance from surface reflectance is negligible. However, thin cirrus and high cumulous clouds are above the majority of atmospheric water vapor and usually contributes detectable radiance.[8] The ideal filter is very narrow and difficult to implement. As a cost savings extra copies of the MODIS[9] filters were used when they became available, although they differed from the ideal in being slightly shorter in center wavelength than the bottom of the absorption band. To compensate for this lack of ideality, these bands will be placed close to the center of the focal plane in order to minimize variation in the spectral response of the band.

3.3 Alternative NIR bands not selected

There are two features in the NIR for which MTI does not provide bands, the absorption feature at about 1.14 µm discussed above and the transmission peak at about 1.25 µm. As with any of the major atmospheric windows, the window at 1.25 µm is potentially useful for surface material identification. However, we were aware of only one direct application of the band, leaf canopy properties,[10] that was of minimal interest to the primary MTI missions. Given the limited MTI focal plane space this band was never considered in detail, although such a band might have been implemented if the absorption feature at about 1.14 µm had been used as the basis for the columnar water vapor retrieval.

4. SHORT WAVE INFRARED BAND SELECTION

4.1 Overview of the SWIR (1.5-3 µm) spectral range

This region was primarily of interest to MTI for vegetation analyses and material identification. The SWIR spectral range is well known in the hyperspectral remote sensing community, primarily because several important minerals (for example carbonatites, gypsum, calcite, and clays) have spectral features in the range from 2.05 to 2.45 µm.[11] It is difficult, however, for multispectral sensors to provide spectral resolution adequate to identify these minerals. The transmission peak around 1.65 µm has proved useful for vegetation characterization, because dry or dead leafs reflect more in band I than in band D. Atmospheric absorption features in this region are generally too strong to be useful for atmospheric characterization, except for cirrus detection. InSb was the detector of choice in the SWIR for MTI, because of its high quantum efficiency and good uniformity, because it allowed utilization of the same detector material from the NIR to the MWIR, and because its cooling requirements were already met due to the requirements of other spectral regions. HgCdTe, PbS, and PtSi were also considered, but relatively high nonuniformity (of HgCdTe and PbS) or low quantum efficiency (PtSi) generally made them unattractive for the MTI systems.

4.2 Selected SWIR bands

MTI has two bands, I (1.54-1.75 µm) and O (2.08-2.37 µm), in the SWIR centered on the two main transmission peaks, at about 1.65 and 2.25 µm, respectively. Band I remained part of the design throughout the design process, because it has been found to be uniformly useful in other sensor systems for vegetation characterization, especially lignin. The peak covered by band O has been found to be a useful indicator of some surface characteristics, e.g., soil moisture and some minerals, that were only weakly related to the MTI mission. This band was on the initial list of the proposed bands, but, as its identifier suggests, was deleted from the list by the time the system requirements were reviewed externally. Subsequent to the review, band O was reinstated. Because the spectral range covered by band O contains several features useful for the identification of minerals, breaking up band O into several bands was briefly considered, but exploitation of this information appeared to require a large number of bands that are very difficult implement using filters and no detailed study of this possibility was examined.

A minor design issue for bands I, and O is the band width. Narrow bands have responses sensitive to detector position on the focal plane, wide versions of the bands are more sensitive to atmospheric water vapor. The MTI bands emphasize the minimization of water vapor effects.

4.3 Alternative SWIR bands not selected

The only alternative in this spectral range that were examined in any detail was the possibility of breaking band O into sub-bands. The team briefly considered replacing the band H filter, with similar cirrus detection bands at 1.8 or 2.7 µm. These alternative bands would allow the utilization of wider bands than the current difficult to implement Band H design, but the lower solar radiance in these bands makes bands implemented at 1.8 or 2.7 µm noisier.

5. MID-WAVE INFRARED BAND SELECTION

5.1 Overview of the MWIR (3-6 μm) spectral range

The MWIR spectral range is often used by the thermal remote sensing community. It has significant thermal emissions, strong temperature dependence, and excellent transmission in the 3.5-4.1 μm atmospheric window, making it of great use in night time surface temperature retrievals. It also potentially offers significantly better spatial resolution than the LWIR for a given aperture size. During the daytime solar reflected signals can exceed natural thermal emissions, greatly limiting its use for thermal retrievals at such times. It is also a useful region for atmospheric retrievals. This spectral range was of interest to the MTI team primarily for its potential for nighttime surface temperature retrievals, but atmospheric retrievals were also considered. InSb is usually the detector of choice in the MWIR as other detectors have similar cooling requirements, but poorer uniformity. HgCdTe was also considered as the detector material for MTI in this spectral range, primarily as a means of limiting the number of detector types.

5.2 Selected MWIR bands

MTI has two bands in the MWIR, J (3.49-4.10 μm) and K (4.85-5.05 μm). J covers the main atmospheric window in this spectral range and hence is essentially the standard band for imaging in the MWIR. The main design concern for this band was how far should the long wavelength edge of the band extend. In the end the detector extended into the atmospheric absorption band to ensure maximum signal at the expense of minor atmospheric contributions to the signal.

K is an unusual band. To the best of our knowledge MTI will be the first satellite sensor to implement a band that overlaps the secondary transmission window in the MWIR near 4.7 μm, see Figure 3. This window is relatively narrow and is poorly transmitting over significant horizontal distances so that is of minor interest at best for non-satellite based sensors. However, path integrated water vapor is smaller for nadir looking satellite sensors so that a significant portion of the radiance in this band can come from the surface. The team therefore investigated this window to see if it would be useful for the MTI mission.

An aspect of the design of band K that raised some concern was its potential sensitivity to variations in atmospheric constituents other than water vapor. As can be seen in Figure 3, the atmospheric window near 5.0 μm is influenced by several atmospheric trace gases. Most of these gases are essentially uniformly mixed in the atmosphere, but H_2O, O_3, and CO have substantial temporal and spatial variations. The main contribution to O_3 is the stratosphere, which is monitored on a global basis and has negligible variation on scales comparable to the MTI field of view. Ozone's contribution on a per scene basis was therefore considered known and effects from its variation considered tractable. The dependence on water vapor was viewed as a plus for this band as it provides information on water vapor concentration if other variables could be known or eliminated. That left CO variability as a possible cause for concern.

CO varies by about a factor of two and is not well monitored in the atmosphere.[12] The atmospheric transmission can therefore vary by about 5% near the CO absorption bands at 4.61 and 4.73 μm due to variations in CO concentration. This dependence on CO variability made the region from 4.54 to 4.81 μm of questionable use to MTI, although, as illustrated by Figure 4, the actual effect on radiance tends to be weak for atmospheres comparable in temperature to the surface. The region below 4.54 μm was not found to be useful so our attention turned to the spectral region above 4.81 μm in the expectation that it would soon be rejected. However, tests on model data showed that a band above the minor radiance minimum at 4.84 μm had a response only weakly dependent on focal plane position, and proved useful in estimating surface temperatures.[13] The band was therefore included in the MTI specification as an experimental band.

5.3 Alternative MWIR bands not selected

The only alternative band in the MWIR that was explicitly examined by the MTI team was the wider version of band K discussed above. There are some other bands of potential use for the study of the atmosphere, the temperature profile in particular, but their exploitation requires more than one such band, and the limited focal plane space made it impractical to consider them in detail.

6. LONG WAVE INFRA~~RED~~ BAND SELECTION

6.1 Overview of the LWIR (6-15 μm) spectral range

The LWIR spectral range is perhaps the most often used thermal IR (3-100 μm) spectral region. It has negligible solar reflected signals, significant thermal emissions, and very good transmission in the 8-13 μm atmospheric window, making it of great use in surface temperature retrievals. It is also a useful region for atmospheric retrievals, because of its water vapor

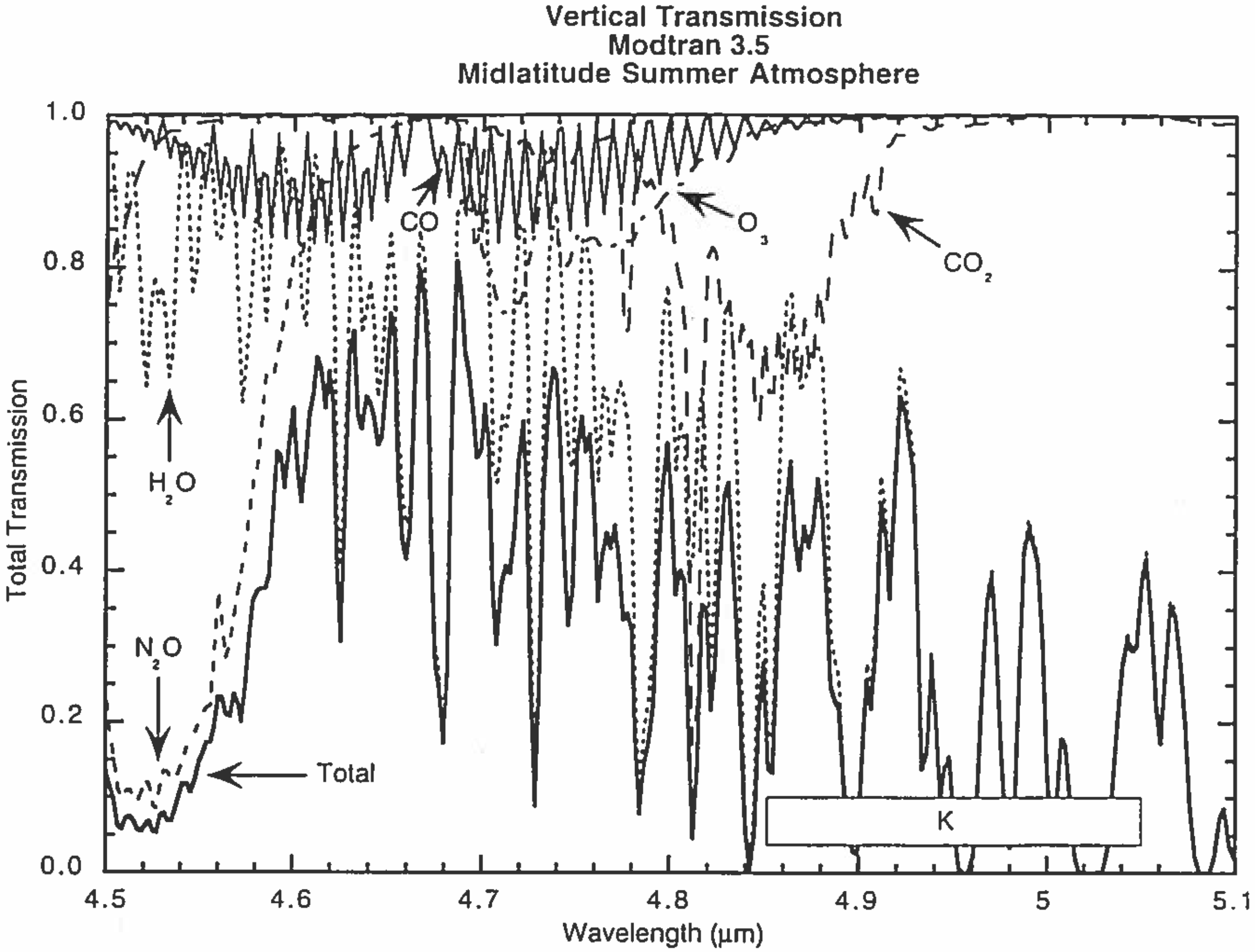

Figure 3. Comparison of band K (box) with atmospheric transmission features in the MWIR.

continuum and ozone absorption features. MTI required operation in this region primarily for daytime surface temperature analyses, although atmospheric information plays a useful supporting role. HgCdTe is usually the detector of choice in this region, as other detectors, for example, Si-BIB arrays, require much colder operating temperatures.

6.2 Selected LWIR bands

MTI has three bands, L (8.01-8.39 µm), M (8.42-8.83 µm), and N (10.15-10.7 µm), in the LWIR. Because of the importance of temperature estimates to MTI's mission, the LWIR was consistently given high priority at all stages of the design process. This spectral region naturally splits into three parts, the window from about 7.9 to 9.3 µm below most ozone absorption, the ozone absorption region from about 9.3 to 10 µm, and the window from 10 to 13.5 µm. The ozone absorption region was viewed as not useful for MTI's mission, so no bands were ever planed for that part of the spectral region. It was usually viewed as desirable to have at least one band on each side of the absorption feature.

The design of the LWIR bands was driven by several constraints that mostly affected band N. For system cost reasons it was considered desirable to use off the shelf technology, the same technology for all three LWIR bands, and minimize the system cooling requirements. Generally the longer the cutoff wavelength of the HgCdTe detector material the less likely it is to be available off the shelf and the noisier it is likely to be at a given operating temperature. It is therefore desirable to use a material with as short a cutoff wavelength as possible. HgCdTe threshold behavior can be difficult to control [illegible] that it was desirable to have detectors with response edges at wavelengths well above the longest band cutoff, or in effect, the longest band cutoff well below the nominal detector edge. It was quickly recognized that these issues, combined with the relative lack of atmospheric spectral structure from 10.1 to 11.5 µm, made it difficult to justify having more than one band above 10 µm.

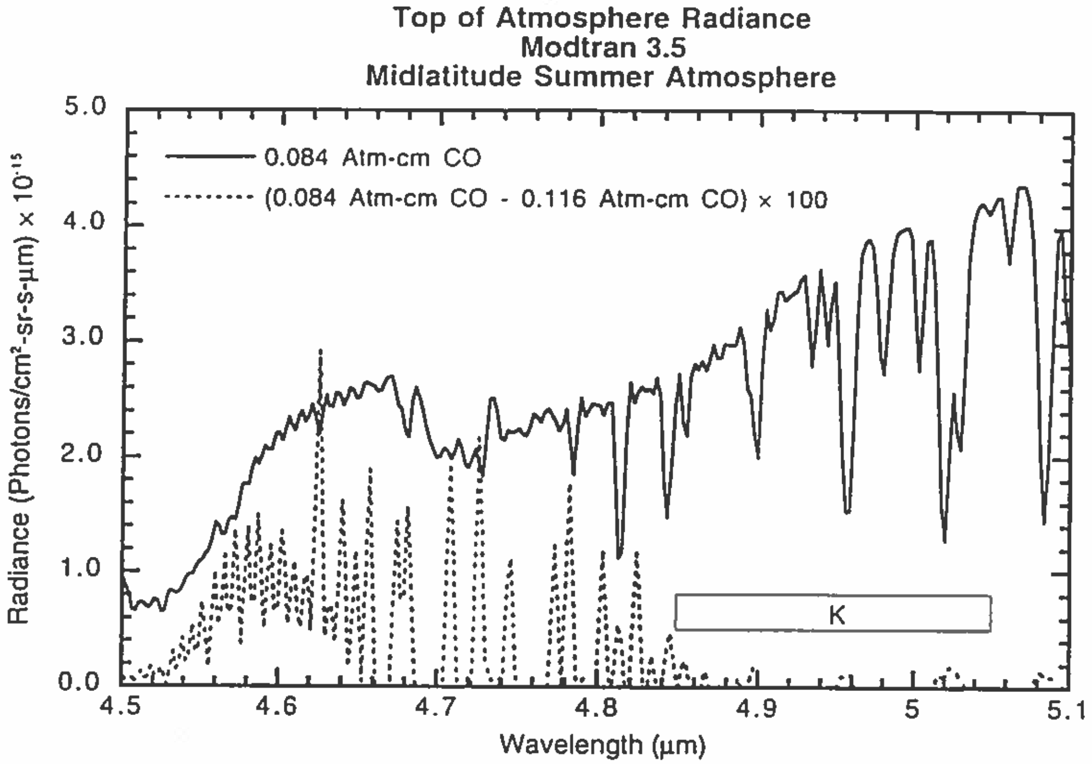

Figure 4. Comparison of band K with the MWIR top of atmosphere radiance.

Initial band specifications gave band N a long wavelength cutoff well above 11 µm, primarily in the expectation that the longer spectral band width would increase signal, and, as a result, improve signal to noise for this band. As system design progressed and the impact of a long wavelength cutoff on other system design issues was recognized the band cutoff was gradually moved to shorter wavelengths. Then it was recognized that radiance levels were so high near the peak in the earth's black body spectrum that the proposed detector implementation used integration times less than the time between readouts in order to keep the system linear. In other words, small changes in the spectral bandwidth of band N had no influence on effective signal levels when other system constraints were included. Therefore, decreasing the cutoff wavelength of band N, by allowing the use of less noisy detectors, would improve signal to noise in all bands, including band N. The long wavelength cutoff for band N was then moved to well below 11 µm to a width that allowed the use of widely available detectors. The result was a band slightly noisier than the optimum, but significantly improved in its noise characteristics over the initial design. The improvement in bands L and M signal to noise was even more dramatic.

The design of bands L and M were driven more by science issues rather than the overall system design issues that influenced band N's design. As can be seen in Figure 5, "average" water vapor transmission is increasing with wavelength from 7.9 µm to about 8.5 µm. As a result, two bands with centers in the ranges 7.9 to 8.5 and 8.5 to 9.3 µm, respectively, could potentially be used for temperature retrieval using a split window technique similar to that used at longer wavelengths for AVHRR.[14] This served as the primary basis for selecting bands L and M. Band L was defined to lie near the center of the 7.9 and 8.5 µm range. In order to minimize the complications due to variations in transmission from the ozone absorption tail above 8.6 µm, also visible in Figure 5, band M was defined to have its center at the low end of the 8.5 and 9.3 µm range. Minor adjustments in their definitions were made to minimize response variations with position on the focal plane.

6.3 Alternative LWIR bands not selected

The only alternative band in the LWIR that was considered in any detail for MTI was a band around 12 µm. Such a band is known to be useful for estimating water surface temperatures using a split window technique,[14] an important MTI mission. However, it was soon recognized that detectors in that spectral range were not available off the shelf, were costly and difficult to produce reliably, and required cooling to below 60 K. As a result, this band was removed from consideration at relatively early stages in the design process.

The design team was aware of bands in this spectral range that are useful for cloud, water vapor, and ozone detection,[9] but none of these bands were examined in any detail. Ozone detection was not considered to be useful for MTI's main missions.

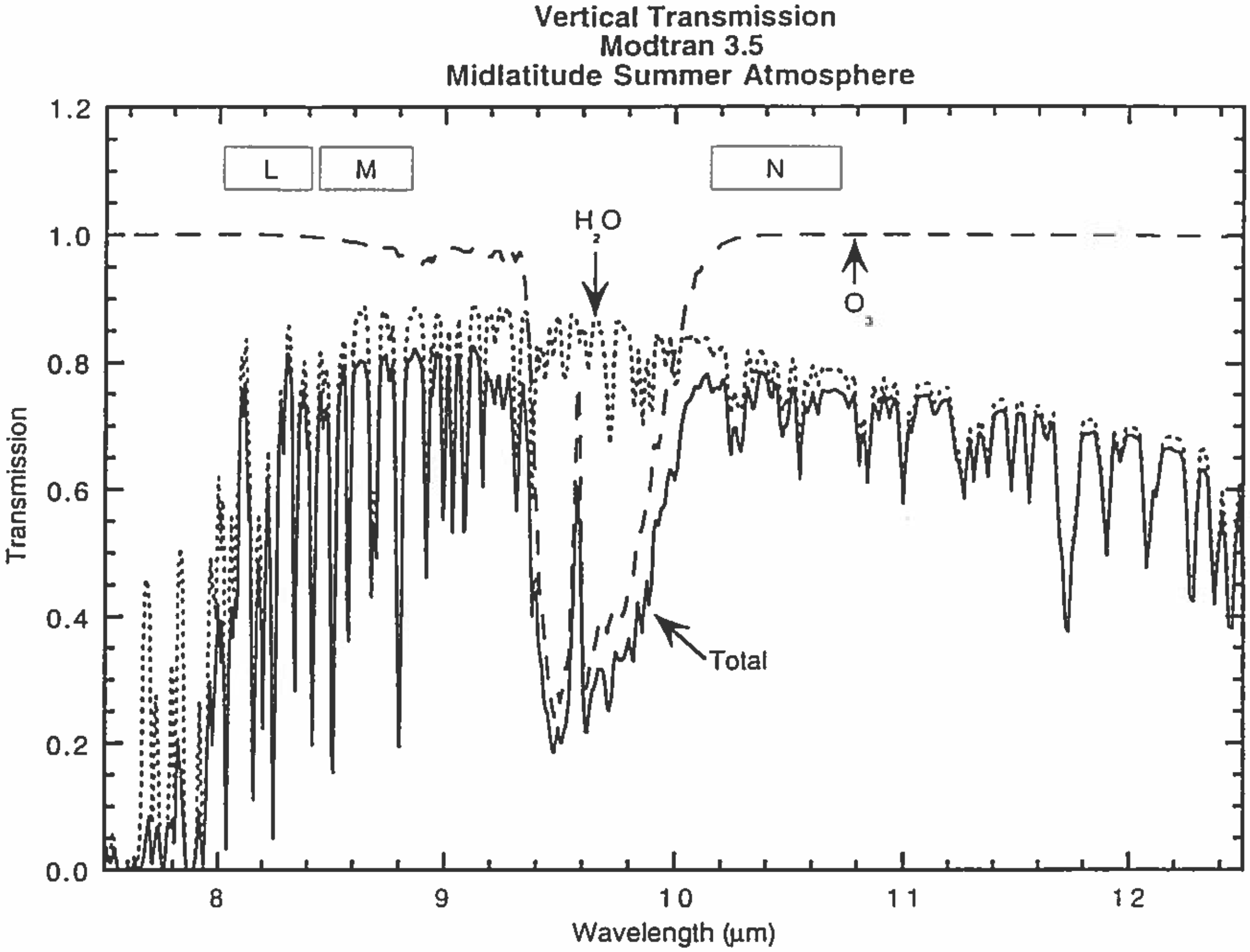

Figure 5. Comparison of bands L, M, N with vertical atmospheric transmission in the LWIR.

The other bands lie in regions that require unusual HgCdTe technology (some with responses above 12 µm), and their proper utilization requires more than one such band. Limited focal plane space and the desire to use off the shelf technology removed those bands from consideration.

7. SUMMARY

The MTI band selection process involved the interaction and resolution of a large variety of conflicting goals and constraints. The primary goal was an imaging multispectral system with particularly well calibrated and high quality imaging capabilities in the thermal infrared. Additional secondary goals included high spatial resolution in the visible and NIR, and the collection of atmospheric information in ancillary spectral channels. Constraints included overall system size and weight, utilization of off the shelf technology, a minimal variety of detector types, single focal plane implementation, and limited on-board storage and downlink capabilities. These constraints made it impractical to implement bands below 0.42 µm or above 11.5 µm, more than twenty bands, or a field of view significantly larger than 12 km.

A detailed modeling effort led to the selection of sixteen bands for implementation that lie well within those constraints. These bands cover portions of the spectrum from 0.45 to 10.7 µm. These bands include four very high spatial resolution bands (A, B, C, and D) in the visible/NIR spectral range, three NIR bands (E, F, and G) for the estimation of atmospheric water vapor, one NIR band (H) for the detection of sub-visual cirrus, two SWIR bands (I, and O) for surface imaging, two MWIR bands (J and K) for surface temperature analysis, and three LWIR bands (L, M, and N) for surface temperature retrieval. One of the MWIR bands, from 4.85 to 5.05 µm (K), appears to be unique with potential for atmospheric characterization.

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9. REFERENCES

1. B. J. Cooke, B. E Laubscher, C. C. Borel, and T. Lomheim, "Methodology for rapid IR multispectral electro-optic imaging system performance analysis and synthesis", *Infrared Imaging Systems: Design, Analysis, Modeling, and Testing*, G. C. Holst, Vol. 2743, pp. 52-86, SPIE, Bellingham, 1996.
2. G. P. Anderson, J. H. Chetwynd, J.-M. Theriault, P. K. Acharya, A. Berk, D. C. Robertson, F. X. Kneizys, M. L. Hoke,. L. W. Abreu, and E. P. Shettle, "MODTRAN 2: Suitability for remote sensing", *Atmospheric Propagation and Remote Sensing II*, A. Kohnle and W. B. Miller, Vol. 1968, pp. 514-525, SPIE, Bellingham, 1993.
3. T. M. Lillesand and R. W. Kiefer, *Remote Sensing and Image Interpretation*, 3rd Ed., p. 432, Wiley, New York, 1994.
4. H. R. Gordon, "Radiative transfer in the atmosphere for correction of ocean color remote sensors", *Ocean Colour: Theory and Applications in a Decade of CZCS Experience*, V. Barale and P. M. Schlittenhardt, pp. 33-77, Kluwer Academic, Dordrecht, 1993.
5. B.-C. Gao and A. F. H. Goetz, "Column atmospheric water vapor and vegetation liquid water retrievals from airborne imaging spectrometer data", *J. Geophys. Res.* 95, pp. 3549-3564, 1990.
6. D. Schläpfer, C. C. Borel, J. Keller, and K. I. Itten, "Atmospheric pre-corrected differential absorption techniques to retrieve columnar water vapor: Application to AVIRIS 91/95 data", *Summaries of the 6th JPL Airborne Earth Science Workshop March 4-8, 1996 Volume 1. AVIRIS Workshop*, R. O. Green, JPL Publication 96-4, Vol. 1, pp. 13-21, National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 1996.
7. R. Frouin, P.-Y. Deschamps, and P. Lecomte, "Determination from space of atmospheric total water vapor amounts by differential absorption near 940 nm: Theory and airboume verification", *J. Appl. Meteorol.* 29, pp. 448-460, 1990.
8. B.-C. Gao, A. F. H. Goetz, and W. J. Wiscombe, "Cirrus cloud detection from airborne imaging spectrometer data using the 1.38 μm water vapor band", *Geophys. Res. Lett.* 20, pp. 301-304, 1993.
9. M. D. King, Y. J. Kaufman, W. P. Menzel, and D. Tanré, "Remote sensing of cloud, aerosol and water vapor properties from the Moderate Resolution Imaging Spectrometer (MODIS)", *IEEE Trans. Geosci. Rem. Sens.* 30, pp. 1-27, 1992.
10. V. V. Salomonson, W. L. Salomonson, W. L. Barnes, P. W. Maymon, H. E. Montgomery, and H. Ostrow, "MODIS: Advanced facility instrument for studies of the Earth as a system", *IEEE Trans. Geosci. Remote Sensing* 27, pp. 145-153, 1989.
11. A. F. H. Goetz, G. Vane, J. E. Solomon, and B. N. Rock, "Imaging spectrometry for earth remote sensing", *Science* 228, pp. 1147-1153, 1985.
12. D. D. Parrish, J. S. Holloway, M. Trainer, P. C. Murphy, G. L. Forbes, and F. C. Fehsenfeld. "Export of North American ozone pollution to the North Atlantic Ocean", *Science* 259, pp. 1436-1429, 1993.
13. C. Tornow, C. C. Borel, and B. J. Powers, "Robust water temperature retrieval using multi-spectral and multi-angular IR measurements", *Proceedings of the International Geoscience and Remote Sensing Symposium (IGARSS'94)*, Pasadena, CA, August 8-12 1994, CD-ROM, pp. 441-443, IEEE, Piscataway, New Jersey, 1994.
14. D. T. L vellyn-Jones, P. J. Minnett, R. W. Saunders, and A. M. Zavody, "Satellite multichannel infrared measurements of sea surface temperature of the N. E. Atlantic Ocean using AVHRR/2", *Quart. J. R. Meteor. Soc.* 110, pp. 613-631, 1984.