Image Registration and Fusion For NASA Remotely Sensed Imagery

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Abstract - *With the increasing importance of multiple platform/multiple NASA remote sensing missions, the integration of digital data from disparate sources has become critical to the success of these endeavors. In the near future, satellite remote sensing systems will provide large amounts of global coverage and repetitive measurements representing simultaneous or multi-temporal observations of the same features by different sensors. Furthermore, with the new trend of smaller missions, most sensors will be carried on separate platforms, resulting in a tremendous amount of data that must be combined. In meeting some of the Earth System Science objectives, the combination of all these data at various resolutions- spatial, radiometric and temporal - will allow a better understanding of Earth and space science phenomena. In this paper, we review some of the most important current and future NASA Earth Science programs and their needs for image registration and fusion. On-going image registration efforts at NASA/Goddard are also described.*

Keywords: Image registration, image fusion, Earth remote sensing data.

1 Introduction

Over the next 30 years, Earth System Science will address issues such as population growth, search for arable land, search for water, and pollution monitoring. Answers to questions such as predicting regional climate change on seasonal and interannual time scales, or understanding the interactions between human activity and the changes in the major Earth ecosystems are needed. To answer such questions, multiple platform/multiple remote sensing missions have been launched or are being planned, and the integration of digital data from disparate sources has become critical to the success of these endeavors. In the near future, satellite remote sensing systems will provide large amounts of global coverage and repetitive measurements representing multiple-time or simultaneous observations of the same features by different sensors. Also, with the new trend of smaller missions, most sensors will be carried on separate platforms, resulting in a tremendous amount of data that must be combined.

Insuring continuity of this data through integration and seamless mosaicking of multiple sensors data – past, present, and future – is very important. It is a key component for building long-term data sets. Very accurate registration of multi-sensor data is the first requirement of such an integration.

Extrapolation among several scales – temporal, spatial, and spectral – is also particularly important for Earth Science studies. This extrapolation enables one to control the size of the minimum detectable change whether spatial, spectral, or temporal, and accuracy in change detection is essential in distinguishing between natural- and human-induced changes. Generally, changes caused by human activity occur at a much faster rate and affect much larger areas. Multi-sensor data fusion is the first requirement of such an extrapolation, at the pixel as well as at the feature level.

More generally, the applications of automatic image registration and fusion dealing with remote sensing data can be summarized as follows:
(1) new sensor calibration and super-resolution, or *multimodal registration and fusion* which enables the integration of complementary information from different sensors;
(2) change detection, and Earth resources surveying, or *temporal registration and fusion* performed to monitor and measure agricultural, geological or land cover features extracted from data obtained from one or several sensors over a period of time. Cloud removal is another application of temporal registration, when observations over several days can be fused to create cloud-free data;
(3) landmark navigation, formation flying and planet exploration, or *viewpoint fusion* which integrates information from one moving platform or multiple platforms navigating together into three-dimensional models; and
(4) content-based or object searching, map updating, or *template registration* which looks for the correspondence between new sensed data and a previously developed model or dataset.
(5) scientific visualization and virtual reality, which creates seamless mosaics of multiple sensor data with multimodal, temporal and viewpoint image fusion.

In this paper, we review some of the current and future NASA Earth Science missions and programs and we will assess their need for image registration and fusion. Some of our early work in image registration is also described.

2 Current and Future NASA Earth Science Missions and Programs

2.1 Programs

Data Acquisition

NASA's Earth Science Enterprise includes many programs among which the Earth Observing System (EOS) is the largest one. This program covers objectives in several domains of Earth Science such as Atmospheric Physics and Land Surface, Oceanography, and Atmospheric Chemistry. The goal of this program is to understand the cause-and-effect relationships among Earth's lands, oceans, and atmosphere and to predict impacts on future climate conditions. To support these programs, a series of satellites has been designed, and the first one, Terra, was launched in December 1999. It includes 5 different instruments, described in section 2.2, which focus on studying Earth's interelated processes but with special emphasis on land measurements. These 5 sensors will take simultaneous measurements about the Earth's atmosphere, lands, oceans, and solar energy balance. The next satellite of the EOS program, Aqua, is planned to be launched late 2000. Similarly to Terra, Aqua's six instruments will focus on studying Earth's interelated processes but with special emphasis on atmospheric temperature and humidity profiles, clouds, precipitation and radiative balance, terrestrial snow and sea ice, sea surface temperature and ocean productivity, soil moisture, and the improvement of numerical weather prediction. Terra and Aqua will have in common two instruments, CERES and MODIS, and since their orbits will cross the Equator at two different times of the day, registering and integrating data acquired by similar instruments but at different times and from different platforms, is of great interest for NASA applications.

Another large program among NASA Earth Science missions is the New Millennium Program (NMP). The purpose of this program is to conduct space flight validation of breakthrough technologies that would benefit future missions. This program supports both Earth and Space Science objectives. One of the first NMP missions is the EO-series of satellites, described in the next section.

Other programs include the Earth Probes, missions with specific orbits or requirements, and the Geostationary Operational Environmental Satellites (GOES) and the Polar Operational Environmental Satellites (POES) programs that provide images used routinely for weather or climate forecastings and storm tracking, but also for long-term model building.

Data Analysis and Management

Success of future Earth and space science missions depends upon increasing the availability of data to the scientific community who will be interpreting space-based observations, and upon favoring interdisciplinary research for the analysis and the use of this data. One of the main challenges in the future of satellite imaging and sensing will be to handle, archive, and store all of these data in a way which can be easily accessible and retrieved by anyone who need to use them. Systems such as the EOS Data and Information System (EOSDIS) [1,2], will require that over one terabyte per day be collected and processed into several levels of science data products within several hours after observation. After 15 years, the estimated amount of collected, processed, analyzed, and stored data will equal about 11,000 terabytes. On the other hand, the wide distribution of satellite data to the general public could be facilitated by regional distribution systems such as the Regional Application Centers, RAC's [3,4] whose goal is to provide local users, such as industry, agriculturalists, urban planners, regional communities, local and "on-time" information about regional applications.

Another challenge will be to analyze this tremendous amount of data, and research in fast computational capabilities is another important aspect which is studied by the High Performance Communications and Computing (HPCC) program. Analysis such as image restoration [5], data compression [6] and data mining [7] are also topics which have to be considered as either pre-processing or in integration to the image registration and fusion processes.

Two other programs for which registration and fusion will play an important role are the Digital Earth (DE) and the Intelligent Synthesis Environment (ISE) programs. The Digital Earth is an interagency program within the US federal government which is described as "a virtual representation of our planet that enables a person to explore and interact with the vast amounts of natural and cultural information centered around the Earth" [8]. The main challenge associated with DE is data management and the technologies that need to be developed to implement a full DE concept include mass storage, high-resolution satellite imagery, high-speed broadband networks, and fast and efficient computational science for image analysis, modeling, simulation and scientific visualization. The ISE program requires development of the same types of technologies but its goal is to create future engineering environments that will be interactive, multisensory, and immersive and that will "allow diverse, geographically dispersed teams to share and transform information into knowledge by combining and analyzing it in new ways" [9]. Such an environment would enable to design future missions by incorporating knowledge of previous missions and knowlege of new or upcoming instruments, hardware, and software technologies, by simulating the mission operation and results, by utilizing virtual reality for visualization, and by collaborating with multi-discipline experts at widely distributed locations.

2.2 Current and Future Missions

Table 1 shows some selected past, current and future Earth Science instruments operating in the wavelength ranges between UltraViolet and Thermal Infrared. As can be seen in this table, these sensors exhibit various redundant and complementary spatial, spectral and temporal resolutions, and therefore a large amount of the data provided by these sensors will have to be registered and integrated either at the data level or at the information level when building long-term models of Earth Science phenomena.

An example for which image registration and fusion are especially important is the study of land cover/land use changes. For such a research objective, Landsat and Landsat-type data such as MODIS and EO-1 data are or will be used. The first Landsat instrument, Landsat-1 was launched in 1972. The Thematic Mapper, TM, first appeared on Landsat-4, launched in 1982, and is still operational on Landsat-5. The ETM+ instrument is an enchanced version of the Thematic Mapper that is carried on the Landsat-7 spacecraft that was launched in April 1999. ETM+ includes all TM features plus additional capabilities such as a panchromatic band with 15m spatial resolution, on-board absolute radiometric calibration, and a thermal IR channel with 60m spatial resolution. The twenty-eight year record of data acquired by the Landsat satellites constitutes the longest continuous record of the Earth's continental surfaces, and this data continuity has been identified by the Land Remote Sensing Policy Act of 1992 as critical to land surface monitoring and global change research. The new ETM sensor and future Landsat instruments respond to this need for data continuity.

More recently, in December 1999, the Terra satellite was launched. Terra is often called the EOS «flagship» and is the first satellite of NASA's Earth Observing System [10]. Terra instruments include :

- ASTER, the Advanced Spaceborne Thermal Emission and Reflection Radiometer which will obtain high-resolution images of the Earth in the Visible, Near-Infrared, Short-Infrared, and thermal-infrared wavelengths. ASTER will be very useful to produce stereoscopic images and as a consequence 3D terrain height data. In comparison to the ETM sensor, ASTER covers approximately the same portions of the spectrum but with a finer radiometric resolution since it contains 14 bands instead of 7, and a finer spatial resolution in the Visible wavelengths of 15 instead of 30 meters.
- CERES, the Clouds and Earth's Radiant Energy System, consists of two broad band scanning radiometers that will measure the Earth's radiation balance and improve these estimates by incorporating cloud radiative properties.
- MISR, the Multiangle Imaging Spectroradiometer, will assess the amount of sunlight that is scattered in different directions in four wavelengths (blue, green, red, and near-infrared) and estimate surface bidirectional reflectance properties at nine different view angles.
- MODIS, the MODerate-resolution Imaging Spectro-radiometer, which will view the entire surface of the Earth every 1-2 days, with 36 spectral bands at spatial resolutions varying between 250m to 1km. MODIS will be very useful to make observations of land and ocean surface temperature, land surface cover, clouds, aerosols, water vapor, temperature profile, and fires.
- MOPITT, for "Measurements of Pollution in the Troposphere," measures carbon monoxide and methane gas levels in the lower atmosphere. These measurements will be utilized to predict long-term effects of pollution and to measure ozone levels in the lower atmosphere.

In the near future, Earth Observing-1 (EO-1) will be the first satellite in NASA's New Millennium Program Earth Observing series, and the first EO mission that will develop and validate instruments and technologies for space-based Earth observations. EO-1's primary focus is to develop and test a set of advanced technology land imaging instruments. Since EO-1 will be inserted into an orbit flying in formation with the Landsat 7, the two satellites will be taking almost simultaneous images of the same scenes. Since EO-1 will carry the ALI (Advanced Land Imager) sensor which includes 6 spectral bands identical to the first 6 Landsat bands, comparison of these "paired scene" images will be one means to evaluate and validate EO-1's land imaging instruments. EO-1 will also share the same orbit as Terra and integration of Landsat-ETM, EO-1/ALI, Terra/ASTER and Terra/MODIS data will be very useful. EO-1 also will represent NASA's first flight of hyperspectral imaging from space with the Hyperion sensor. An atmospheric corrector (LAC) also is on the satellite platform. EO-1 will thus present three different, but complementary sensor platforms with varying spatial resolutions offering a rich test bed for image fusion concepts. The complementary use of the thermal IR Landsat channel and new hyperspectral observations from EO-1 also present unique opportunities for improving surface flux or property assessment if the fusion problem can be solved [11].

3 Current Work on Image Registration

While navigation often refers to "systematic correction", image registration refers to "precision correction." The systematic correction is usually model-based and takes into account information such as satellite orbit and attitude, sensor characteristics, platform/sensor relationship, and Earth rotation and curvature. On the other hand, precision correction is usually feature-based; starting from the results of the systematic correction (usually accurate within a few pixels), it utilizes selected features or control points to refine the geo-location accuracy within one pixel or a sub-pixel. Precision correction is either implemented as a post-processing to the systematic correction, or systematic and precision corrections are integrated in a closed-loop where the results of the precision correction are utilized to refine the navigation model. We will focus on precision correction or automatic image registration of the data as post-processing to systematic correction. For applications such as data fusion, it is very important to reach the sub-pixel accuracy that can be achieved by precision correction.

As a general definition, image registration is described as the process that provides the "relative" orientation of two images (or one image and other sources, e.g., a map), with respect to each other, from which the absolute orientation into an absolute reference system can be derived. Usually, image registration includes three main steps [12]:

(1) feature extraction to be used in the matching process,
(2) feature matching strategy and metrics,
(3) resampling of the data based on the correspondence computed from matched features. For some applications, this step is replaced by an indexing of the incoming data into an absolute reference system, e.g. (latitude, longitude) reference system for Earth satellite data. When several data are integrated, the resampling step is replaced by the fusion process, and if necessary resampling is performed.

Our on-going work at NASA/Goddard mainly focuses on the evaluation of different feature extraction and feature matching techniques within the registration framework.

Feature Extraction Evaluation

Assuming the transformation to be either rigid or affine, and using either spatial or spectral correlation, a preliminary study has been performed with the goal of evaluating the accuracy and the computational timing of methods using features such as gray levels, edge features, or wavelet features [13,14]. In this study, all methods are compared to a semi-manual registration similar to the method most commonly utilized for registration; a human operator "manually" selects Control Points in two images, and these points become the input to compute the deformation model between the two datasets. The transformation is chosen by the user as either a rotation, a translation, a rigid, affine, or polynomial transformation.

Gray levels are matched using either a spatial correlation or a phase correlation. With spatial correlation, the input image is shifted over a search grid and multiplied times the reference image. The search grid location that produces a maximum from the image multiplication is taken as the best amount of shift for registration. Our implementation also includes a refinement process which allow for the detection of the image shift location to a quarter pixel resolution. On the other hand, phase correlation is a mathematical technique that was developed to register images in which the misregistration is only a translation. The technique can be described as follows: given a reference image, g_R and a sensed image g_S, with 2-D Fourier transforms G_R and G_S, respectively, the cross-power spectrum of the two images is defined as $G_R G_S^*$ and the phase correlation function, d, is given by the inverse Fourier transform of that spectrum. The spatial location of the peak value of the phase correlation function d, corresponds to the translation misregistration between g_R and g_S.

When using edge features, the registration is performed in an iterative manner, first estimating independently the parameters of the deformation transformation, and then iteratively refining these parameters. For this implementation, we chose to model the transformation as a combination of a scaling in both directions, a rotation and a shift in both directions. This algorithm is based on the assumption that rotation angle and scaling parameters are small (within 5 degrees for the rotation angle and within [0.9,1.1] for the scaling parameters). At each iteration, the five parameters are retrieved by computing the cross-correlation measures for all successive values of the parameters taken at incremental steps (see more details in [15,16]).

While edge detectors highlight points of high intensity contrast, wavelet transforms provide a multi-resolution representation of the images into components of different frequencies. This multi-resolution nature of wavelets provide considerable advantages such as computational speed-up as well as a reliable way to compare multiple resolution data from different sensors. Wavelet transforms provide a space-frequency representation of an image. For the wavelet-based registration used in our preliminary evaluation study, only discrete orthonormal basis of wavelets have been considered and are implemented by filtering the original image by a high-pass and a low-pass filter, thus in a multi-resolution fashion. At each level of decomposition four new images (each half the size of the original) are computed. They represent low- or high-frequency information for both horizontal and vertical directions. The process is iterated by starting again from the low-frequency compressed images, thus building a hierarchy of lower and lower resolution images. After decomposing reference and input images, our wavelet-based registration extracts at each level of decomposition domain independent features. These features are used to compute the transformation function by following the multiresolution approach provided by the wavelet decomposition. Features are either chosen as the grey levels provided by the low-frequency compressed versions of the original image (for non-noisy images), or are based on the high-frequency information (e.g., maxima points) extracted from the wavelet decomposition [17,18].

Defining intercomparison criteria is a relatively difficult task, since each application might have different requirements and the importance of the criteria might vary from one application to the next. The main criterion on which these first results are focusing is the "accuracy" measurement. Different methods can be thought of to quantify the accuracy of a given registration method. In this study, the "true" transformation is known for two first datasets and manual registration will be utilized as partial ground truth for a third dataset. Computational requirement is another criterion used for evaluation. The four automatic registration algorithms described previously were applied to the three datasets. Results of this first evaluation can be seen in [13,14], but the results are summarized here. Accuracy results show that edges or wavelets features are more reliable than gray levels. Computational results show that, by utilizing the multi-resolution nature of wavelets, a wavelet-based registration is much faster than an edge-based registration. Although, if the user is only looking for translations, phase correlation can provide a very fast answer, the wavelet-based method is the most general in searching for rotations and translations.

Looking more carefully at wavelets, we know that, according to the Nyquist criterion, in order to distinguish between all frequency components and to avoid aliasing, the signal must be sampled at least twice the frequency of the highest frequency component. Therefore, as pointed out in [19], "translation invariance cannot be expected in a system based on convolution and subsampling." When using a separable orthogonal wavelet transform (such as Daubechies's filters), information about the signal changes within or across subbands. This brings a lack of translation and rotation invariance to the wavelet representation, which means that the wavelet transform does not commute with the translation or the rotation operator [20]. This property could be detrimental to the use of wavelets for image registration. So, following these remarks, we conducted a study where the use of wavelet subbands was quantitatively assessed as a function of features' sizes. The study reported in [21] shows that when using cross-correlation, the wavelet-based registration method described previously is still a useful registration scheme in spite of translation effects. The results are summarized here, see [21] for more details:

• the low-pass subband is relatively insensitive to translation, provided that the features of interest have an extent at least twice the size of the wavelet filters.

• the high-pass subband is more sensitive to translation, but peak correlations are still high enough to be useful.

Following this study, we considered rotation- and translation-invariant overcomplete steerable filters developed by E. Simoncelli [19] in order to create the feature space. We kept the same correlation framework for the only purpose of comparing Daubechies and Simoncelli filters under the same conditions and for registration purposes, and we integrated Simoncelli's filters in our wavelet-based image registration scheme. Utilizing synthetic data as well as data from the Landsat/ Thematic Mapper (TM) and from the NOAA Advanced Very High Resolution Radiometer (AVHRR), we observed that, as expected and due to their translation- and rotation-invariance, Simoncelli filters perform better than Daubechies filters [22,23]. In particular, steerable filters show better robustness to larger amounts of noise than orthogonal filters. The comparison of Simoncelli-wavelet features with edge features and other translation-invariant wavelet features still remains to be done. Other features such as region centroids [24] or corners also need to be investigated.

Feature Matching Evaluation

The second step, feature matching, is now the principal focus of our image registration investigations. When the size of the data or the number of transformation parameters increases, (e.g., for an affine transformation), the number of computations involved in an exhaustive cross-correlation search increases exponentially. Therefore, other feature matching methods have to be considered. Among these methods, optimization gradient-descent methods have been extensively utilized for medical image registration [25,26] and we are now evaluating the use of these methods for remote sensing image registration [27]. Gray levels, edge magnitudes or wavelet low-frequency information could be used as input to these optimization methods. We are also looking at using Mutual Information as an input to matching by optimization. Mutual information, or relative entropy, is a basic concept from information theory which measures the statistical dependence between two random variables; or equivalently it measures the amount of information that one variable contains about another [28]. Therefore optimizing the mutual information between two images can be a very powerful tool to register satellite images.

We also studied the use of a statistically robust feature matching method based on the use of nearest-neighbor matching and a generalized Hausdorff distance metrics. This method is based on the principle of point mapping with feedback. Specifically, given corresponding sets of control points in the reference and the input images within a prespecified transformation (e.g., rigid, affine), this method derives a computationally efficient algorithm to match these point patterns. Two algorithms measure distances with the partial Hausdorff distance and derive the matching transformation either by a geometric branch-and-bound search of transformation space or by using point alignments. See [29] for details. This method has been applied successfully to Simoncelli overcomplete wavelet features and very good results have been obtained for registering Landsat data [30].

In summary, our registration studies focus on characterizing the best type of features (edges, wavelets, region centroids or mutual information) and the best type of feature matching (correlation, gradient descent, robust feature matching or even genetic algorithms) to perform registration of NASA remote sensing data. Ultimately, the algorithm intercomparison will be based on the following criteria: accuracy, adaptability to multiple sensors, level of automation, computational requirements and adaptability to large datasets.

4 Needs for Image Fusion

According to many authors [31-34], «by using redundant information, image fusion may improve reliability, and by using complementary information, image fusion improves capability.» Image fusion aims at obtaining information of greater quality, with the exact definition of 'greater quality' depending upon the application. The Earth System Science era will drive the need for image fusion methods exponentially not only because of the greatly expanded suite of sensors across all spatial, spectral, and temporal domains, but also because of the increased sophistication of the use of the information from these sensors. We are pushing the sensors to provide more information about parameters to drive complex process-oriented models of the biosphere, hydrologic, oceanic, and atmopsheric dynamics. The increased complexity and robustness of the models require prodigious numbers of input parameters which can only be derived from mutiple wavelengths at multiple resolutions. Sophisticated data assimilation methods are used to combine model predictions and satellite data for overall improved estimates or to fill missing gaps in the data records. More and more, users will extract one set of model input parameters from one satellite record and other parameters from other satellite records to derive improved estimates of such time varying properties as vegetation structure and carbon uptake [35]. Inverse methods are notoriously sensitive to missregistration and other small errors in observations. Formal data fusion methods play an important role in minimizing these noise variations.

Evaluation of different fusion methods can only be done on an application-to-application basis. In the near future, we intend to look at different fusion algorithms and evaluate them in the framework of the two following applications, which would be of great interest to land transformation studies:

- improving image classification by fusing data of multiple spatial and spectral resolutions,
- improving change detection through super-resolution of fused data taken from multiple viewpoints.

Traditionally, many applications of image fusion with NASA based sensors involve applying a panchromatic sharpening band and a few multispectral bands. The high spectral resolution allows for the identification of materials in the scene, especially with forthcoming hyperspectral sensors, while the high spatial resolution bands more precisely locate the materials. Accurate image fusion relies on the spectral correlation between the bands with highly correlated bands being easiest to fuse. With the plethora of new sensors across all the regions of the spectrum, different approaches have been taken to model the relationship between the multispectral bands and the sharpening band when the correlation between bands are more difficult [36]. Traditional examples include multiresolution analysis [37], high-pass filtering [38] and simple ratio methods [39]. The expanded number of wavelengths available also permit use of novel spectral unmixing methods to extract end member signatures at one resolution and apply them at different spatial resolutions [36,40,41].

Image fusion is often described as being performed at three different levels: pixel-, feature-, and decision- levels. At the pixel-level, several statistical/ numerical fusion methods have been proposed in the litterature and include: arithmetic combinations, Principal Component Analysis (PCA), High Pass Filtering, Regression Variable Substitution (RVS), Canonical Variate Substitution, Component Substitution, and Wavelet Transforms. Since PCA enables a decrease in the number of channels by reducing the inter-channel dependencies, this type of data reduction will be especially useful for unsupervised segmentations and for neural network classifications of multiple data. The RVS method is used to determine a linear combination (replacement vector) of an image channel that can be replaced by another image channel. Multi-resolution pyramids and wavelet transforms have also been used to perform pixel-level fusion [42-44]. Since wavelet transforms describe images in the frequency domain at multiple spatial resolutions, performing image fusion within a wavelet framework enables to fuse data selectively at various frequency components in the lower spatial resolutions, while preserving the spectral information of higher spatial resolutions. When dealing with textured areas, wavelet features associated with gray levels may improve neural network classifications [45].

5. Need for Fast Implementations

Current microprocessor based architectures do not have the flexibility or processing throughput to meet the new performance requirements necessary for fast on-the-ground or on-board processing systems. A large part of our research is being devoted to implementing our image registration and fusion methods on parallel computers. Previous work involve the use of massively parallel architectures such as the MasPar MIMD machine and the Cray T3E computer [46,47]. We are also studying systems that take advantage of reconfigurable Field Programmable Gate Array (FPGA) computers and that have significantly higher performance than traditional systems. Systems built with these chips are sometimes called “soft hardware” and can be changed as easily as software. We already implemented a cloud detection algorithm (ACCA) used for Landsat processing on an FPGA Wildforce board built by Annapolis Microsystems. The implementation of the first step of the ACCA algorithm yields interesting results: the system performs step one in 0.012 seconds while we estimated that an SGI (300 MHz) machine would take about 0.050 seconds [48].

Concurrently, since FPGA-based systems are still limited by I/O bandwidth, and might not be applicable to all classes of algorithms, we are also investigating the next generation of Commercial-Off-The-Shelf (COTS) Beowulf-class parallel computers, which are clusters of PC’s running parallel Linux. An example of such a system is the HIVE, a cluster of 64 nodes which has reached up to 10.2 Gflops for some applications. Computations done for the Advanced Geosynchromous Studies (AGS) show that an edge-based image registration with a cubic interpolation resampling would require about 700 floating point operations per pixel. If we imagine processing an hyperspectral scene (e.g., 7000 square pixels by 250 bands) every 3 minutes, it would require a 48 Gflops processing system [16]. Both types of architectures, FPGA’s and Beowulf Clusters, offer the potential of a dramatic increase in on-board flight processing capability by taking advantage of parallel processing while lowering the complete mission cost.

6. Conclusion

In summary, current and future NASA missions will generate terabytes of data that represent redundant and complementary information. This large amount of data will need to be integrated in order to study the Earth as a dynamic system, resulting in a better understanding of the interactions between humans, the atmosphere, and the biosphere. The episodic nature of most interesting events would cause them to be missed if the data were not being gathered continuously. Comprehensive data sets will allow scientists to construct and evaluate complex models of many Earth-related processes. But currently, due to computation and time constraints, only a small percentage of the data gathered by remote sensing is actually viewed by an individual user. Also, data gathering missions tend to be multidisciplinary, so different aspects of the data sets are pertinent to different researchers. Efforts need to be pursued to register, organize, and fuse all this data so that it becomes more accessible and easier to manipulate. Image registration and fusion will also be of great interest to perform navigation and planning of formation flying systems. From an image processing point of view, all these reasons drive the need for accurate image registration and fusion. Realistic and accurate scientific visualization will also make use of such capabilities. Simultaneously, the large amount of data to be processed as well as the need to perform these applications on-board spacecraft or for planetary exploration will drive the need for automatic and fast implementations on high-performance computers.

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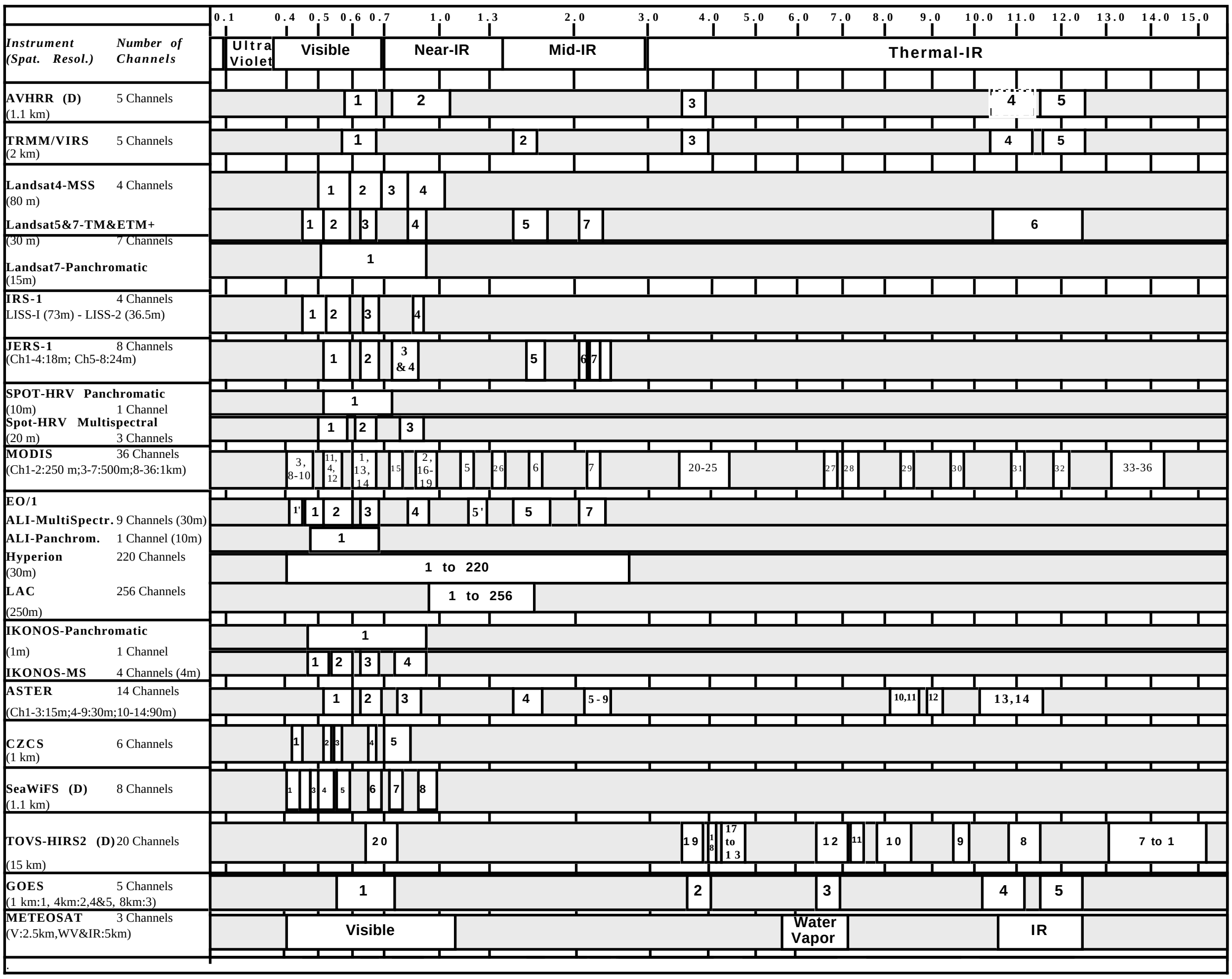

Table 1

Selected Current or Future Instruments (UltraViolet to Thermal Infrared Wavelengths)