XGOHI, Extended GOES High-Inclination Mission for South-American Coverage

Shahram Tehranian[1], James L. Carr[2], Shu Yang[2], Anand Swaroop[1], Keith McKenzie[3]

[1]Nortel Government Solutions (NGS)
[2]Carr Astronautics
[3]National Environmental Satellite Data Information Service (NESDIS)
National Oceanic and Atmospheric Administration (NOAA)

Abstract – Operational weather forecasting depends critically on the Geostationary Operational Environmental Satellite (GOES) system. The GOES constellation consists of an eastern satellite stationed at 75°W longitude, a western satellite stationed at 135°W longitude, plus in-orbit spares. As of mid-2005, GOES-12 occupied the eastern slot, GOES-10 occupied the western slot, and GOES-11 was in storage in orbit. National Oceanic and Atmospheric Administration (NOAA) plans to replace GOES-10 with GOES-11 as the operational GOES-W satellite in late-2006. The GOES-10 satellite is still functioning well, but has exhausted its north-south station-keeping fuel. GOES-10 will be drifted east to its new station at 60° W longitude where it will continue to operate in a high-inclination mission to provide coverage over South America and off the west coast of Africa where hurricanes are born. Other satellites may also be operated in high-inclination missions when they exhaust their station-keeping fuel, extending their operational lifetimes and enhancing the return on the public investment in the GOES system. Normally, the GOES Imager is operated in fixed-grid mode, meaning that Image Motion Compensation (IMC) is applied in space to control the Imager scan mirror to compensate for image distortion caused by deviations of the orbit and attitude from their reference values. Considering that the Sounder is operated in dynamic-gridding mode, no IMC is applied to control its pointing. Current GOES operational spacecraft (east and west) operate within a 0.5 degree inclination limit that allows the on-board IMC system to scan imagery as if from a *perfect GOES projection* from a fixed point in orbit. This limitation on inclination, limits the life of GOES spacecraft in that older spacecraft (with lower fuel reserves) cannot be maintained within the 0.5 degree inclination limit. A study commissioned by NOAA during the spring of 2005 reported that ground remapping (effectively applying IMC on the ground) would allow continued operations of older spacecraft, while preserving the benefits of fixed-grid mode. Hence the same quality of Image Navigation and Registration (INR) service provided normally would be transparently delivered. The proposed remapping of images has been employed on Meteosat and Meteosat Second Generation (MSG) for many years and is also part of the Japanese MTSAT Program. Continuous operation of GOES-10 in a high inclination mode using this new ground-based IMC capability will dramatically improve the quantity and quality of data available to South American countries for improving weather forecasts, limiting the impact of natural disasters, and improving energy and water resource management. The scope of this paper is to describe the design and implementation of the operational ground system needed to support the eXtended GOES High-Inclination (XGOHI) mission.

Index Terms – GOES, Ground System Processing, Image Motion Compensation (IMC), Resampling, Remapping

I. INTRODUCTION

The Operations Ground Equipment (OGE) for the Geostationary Operational Environmental Satellite (GOES) spacecraft consists of components located at the National Oceanic and Atmospheric Administration (NOAA) Command and Data Acquisition (CDA) stations (CDAS) at Wallops Island, Virginia and the Satellite Operations Control Center (SOCC) in Suitland, Maryland. The Extended Sensor Processing System (ESPS) [1-3] is the functional element of the OGE responsible for the real-time ingest and processing of the GOES sensor data producing the GOES Variable (GVAR) [4] data stream. The ESPS also provides input to the orbit and attitude determination function, contained in the Orbit and Attitude Tracking Subsystem (OATS), by performing range measurements, processing sensor star view data, and extracting periodic Image Motion Compensation (IMC) and servo error data for transmission to OATS. The ESPS ingests raw imager and sounder data from the spacecraft via the OGE Data Acquisition and Patching Subsystem (ODAPS) and performs the functions necessary to generate a GVAR-formatted data stream for real-time transmission through the ODAPS back to the GOES spacecraft. The spacecraft, in turn, relays that data to the primary user receiver stations. A diagram showing the ESPS in relation to the rest of the GOES ground system is presented in Figure 1.

The United States normally operates two meteorological satellites in geostationary orbit over the equator. Each satellite views almost a third of the Earth's surface: one monitors North and South America and most of the Atlantic Ocean, the other North America and the Pacific Ocean basin. GOES-12 or GOES-East is positioned at 75° W longitude and the equator, while GOES-10 or GOES-West is positioned at 135° W longitude and the equator. The two operate together to produce a full-face picture of the Earth, day and night. Coverage extends approximately from 20° W longitude to 165° E longitude.

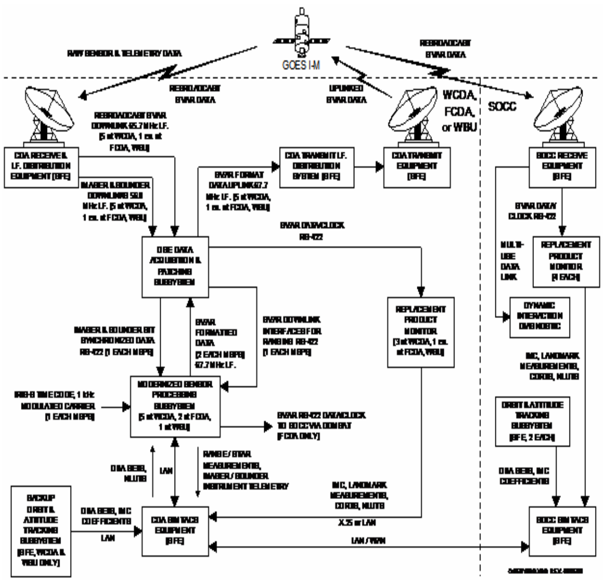

Figure 1: ESPS interface diagram

The main mission is carried out by the primary instruments, the Imager and the Sounder. The imager is a multi-channel instrument that senses radiant energy and reflected solar energy from the Earth's surface and atmosphere. The Sounder provides data to determine the vertical temperature and moisture profile of the atmosphere, surface and cloud top temperatures, and ozone distribution.

The GOES-10 satellite will be replaced by GOES-11 as the operational GOES-W satellite by the end of 2006. The GOES-10 satellite is still functioning well, but has exhausted its station-keeping fuel. GOES-10 will be drifted east to its new location at 60° W longitude, where it will continue to operate in a high-inclination mission to provide coverage over South America as part of NOAA's Earth Observation Partnership of the Americas (EOPA). This is expected to help protect lives and property in Central and South America by significantly improving satellite detection of severe storms, floods, drought, landslides, volcanic ash clouds, wildfires and other natural hazards. Continuous operation of GOES-10 in a high inclination mode using a new ground-based motion compensation capability will dramatically improve the quantity and quality of data available to Latin American partners for improving weather forecasts, limiting the impact of natural disasters, and improving energy and water resource management. Other satellites may also be operated in high-inclination missions when they exhaust their station-keeping fuel, extending their operational lifetimes and mitigating the risk to NOAA in case the GOES-R generation of satellites is deployed later than planned.

In Section 2, we describe GOES high inclination mission operations concept including Earth coverage, resampling process, data latency and radiometric impact, respectively. Section 3 describes the system architecture for the ESPS while section 4 describes a Test Image Simulator (TIG) for the geometric verification of resampled images. Section 5 concludes the paper and comments on future directions for this work.

II. HIGH INCLINATION MISSION OPERATIONS CONCEPT

Implementation of Image Motion Compensation (IMC) on the ground through resampling is an integral part of the high-inclination mission operations concept. The objective of the on-ground IMC implementation is to provide the same level of Image Navigation and Registration (INR) performance that is achieved with on-board IMC. Resampling is not new to meteorological satellite systems. It has been employed on the European geostationary METEOrological SATellite (METEOSAT) [5] and METEOSAT Second Generation (MSG) [6] for many years and resampling is also part of the Japanese Multi-functional Transport Satellite (MTSAT) program.

Normally, the GOES Imager is operated in fixed-grid mode, meaning that IMC is applied in space to control the Imager scan mirror to compensate for image distortion caused by deviations of the orbit and attitude from their reference values. In fixed-grid mode, the relationship between GVAR line and pixel coordinates and latitude and longitude is standard and invariant. Users benefit in that they do not need to navigate images using a complicated description of the orbit and attitude. Instead, users navigate images as if the satellite were on the equator at a fixed longitude and oriented towards the Earth with all attitude angles zero. In addition, the image geometry is stable; movie loops will show clouds moving but the land fixed. Normally, the Sounder is operated in dynamic-gridding mode, meaning that no IMC has been applied (IMC is disabled) to control its pointing.

A. Earth Coverage

Earth coverage is impacted by the higher inclination in two ways. First, coverage is lost at the extreme northern and southern limbs, as pixels slip over the horizon, depending on the orbital phase with respect to the nodal crossing. This is unavoidable and cannot be corrected for. More practically, as limb data is of little use, the prime coverage zone (within about 60° Earth Central Angle (ECA)) will oscillate north-south over the course of a day. Full-time (*i.e.*, 24-hour-a-day) coverage of a latitude range equal to the inclination is thereby lost at the northern and southern extremes of the prime coverage zone. This effect is present at low inclination too, but it is obviously less important. Figure 2 shows the orbital inclination for GOES-10 as time progresses. Figure 3 shows the two extreme coverage circles for ECA < 60° when the orbital inclination is 3°.

The second effect pertains to targeting of frames that are not Full-Disk (FD) frames. Obviously, FD frames will continue to be fully covered but other frames (*e.g.*, CONUS or storm tracking frames) will need to be targeted or over-scanned to achieve the desired coverage. In the case that a frame is over-scanned, some data will be lost to trimming required to form a rectangular resampled image frame. On the other hand, without over-scanning, there will likely be a need to insert *fill* pixels into the resampled frames because of a lack of data from which to construct certain resampled pixels.

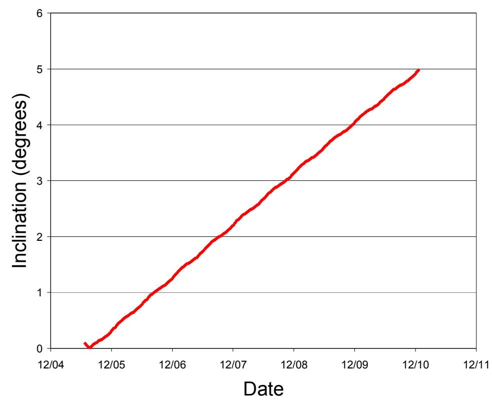

Figure 2: GOES-10 orbital inclination versus time

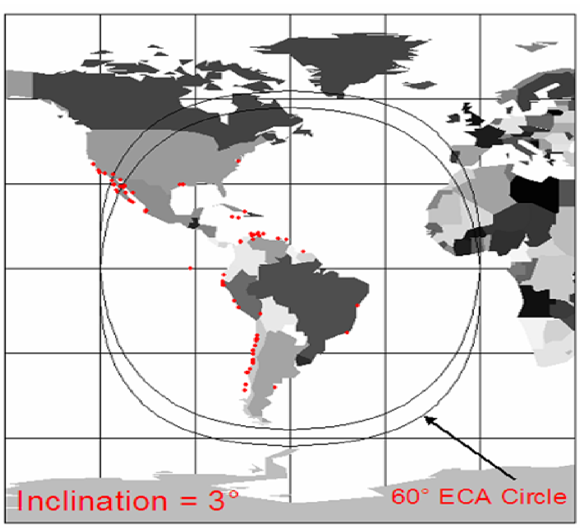

Figure 3: Earth coverage for 3° inclination and station at 60° W

B. ***Resampling Process***

There are several resampling methods that may be considered. The simplest is Nearest-Neighbor (NN) resampling, whereby the nearest real pixel value to the resampled pixel is used as the resampled pixel value. In general, the locations of resampled pixels will map to non-integer line and pixel numbers in the raw images; therefore, NN resampling introduces geometric quantization noise of $\pm$ 1/2 pixel. Bicubic resampling is only one example of a high-order resampling method. Fundamentally, all such high-order resampling methods are convolutions of raw image pixels with resampling kernel functions. There is first a horizontal resampling step and then a vertical resampling step as shown in Figure 4. Resampling is, therefore, a Digital Signal Processing (DSP) algorithm [7]. The kernel functions have an impact on the resampled image Modulation Transfer Function (MTF) and Signal-to-Noise Ratio (SNR) [8]. The kernel design can accomplish a desired modification of the MTF and SNR, or the kernel can be designed so as to minimize the impact of resampling on MTF and SNR. The ESPS design is envisioned to allow for flexibility in the resampling kernel used from NN to, 4-point bicubic, and up to 32-point kernels. The selection of horizontal and vertical resampling kernels can be done independently of the implementation of resampling in the ESPS. As shown in Figure 4, a column of intermediate pixels is first created in a horizontal resampling step, and then the final resampled product pixel is created with a vertical resampling step. Each resampled pixel is created from a convolution of the input (either raw or intermediate) pixels with a resampling kernel.

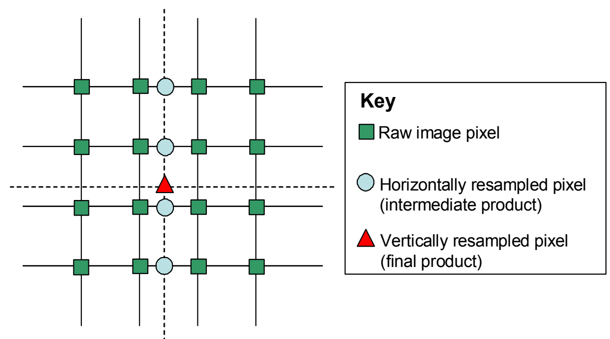

Figure 4: Resampling process

C. ***Data Latency***

Additional latency in data delivery will necessarily be introduced in the high-inclination mission. There will also be latency added by the resampling process, but this should be much smaller than the latency added by the need to wait for the acquisition of all the necessary pixels. The ESPS must wait until all necessary pixels are acquired to complete the resampled line. Figure 5 shows how the waiting time within the ESPS increases proportionally with the orbital inclination.

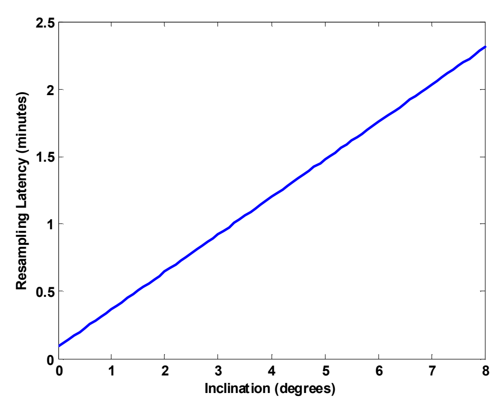

Figure 5: Waiting time due to orbital inclination

D. Radiometric Impact

The radiometric impact of resampling has already been discussed in terms of SNR. The overall gain of the resampling process and the mixing of data from detectors with possibly different gains and offsets are other considerations. The overall gain of the resampling process is determined by the resampling kernel. The resampling gain should be set to unity to preserve the radiometric calibration of the instrument. This represents an important constraint on the kernel design. Gain equalization between detectors is important to remove image striping, which may be a problem for certain flight instruments but not for others. To mitigate striping, the ESPS calibrates the Infrared (IR) detectors individually and can apply a Normalization Lookup Table (NLUT) to each of the Visible (VIS) detectors. Each VIS NLUT is constructed so as to match the radiometric histogram of a detector to that of a reference detector. This represents a statistical equalization of the gain of each VIS detector, rather than a true calibration.

The IR calibration and the VIS NLUT should be applied to each detector prior to resampling, even though resampling, as it mixes data from different detectors, will tend to equalize the gains. The VIS NLUT for each detector should, therefore, be developed from the raw, rather than the resampled, pixels.

III. SYSTEM ARCHITECTURE

The core components of ESPS are the GOES Ingest Unit (GIU), GOES reSampling Unit (GSU) and the GOES Ranging Unit (GRU), which primarily function as a real-time front-end for the ESPS. The GIU and GRU perform data ingest, calibration, and GVAR output formatting functions for both the Imager and Sounder instruments, while the GSU provides on-ground image motion compensation for the imager sensor data. The GIU uses EDT GP-20 [3] cards to ingest raw Imager and Sounder data. Imager data enters the GIU at a rate of approximately 2.6 Mbytes/sec [1]. The Sounder data rate is approximately 40 Kbytes/sec [1]. The GVAR formatted processed data is up-linked by the GRU to the satellite via a separate EDT GP-20 [3] card. Ranging is also accomplished in the GRU through timing comparison of up-linked and down-linked GVAR streams. The ESPS allows IMC to be applied on the ground through resampling within the GSU. Resampling is driven by the Orbit and Attitude (O&A) data sent to the ESPS by the Orbit and Attitude Tracking System (OATS).

IV. TEST IMAGE SIMULATOR (TIG)

Figure 6 shows the unit test configuration for geometric verification of resampled images. A Test Image Simulator (TIG) creates Infrared (IR) and Visible (VIS) images while the resampling module resamples the simulated images to create images in fixed coordinates. An image analysis tool is the used to compare the resampled images with the source image to verify the geometric correctness of the implementation of the resampling algorithm.

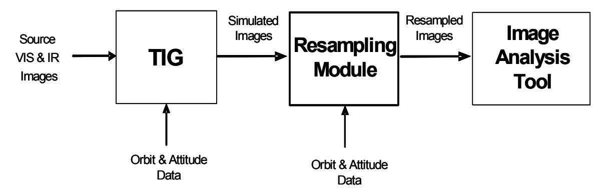

Figure 6: Test configuration for geometric correctness of resampled images

Figure 7 shows the satellite orbital view at six-hour intervals used in the simulation. Figures 8 to 12 show the original GOES image and images simulated at six-hour intervals at an inclination angle of 4˚. The original image is an IR image with 1000 lines by 1500 pixels. Simulated images are compared to the original in order to illustrate the view difference on a high inclination orbit. The simulated images are used to verify the geometric correctness of the implementation of the resampling algorithm. Hence the simulated images by the TIG may feed into the resampling module producing an output which will be compared to the original image.

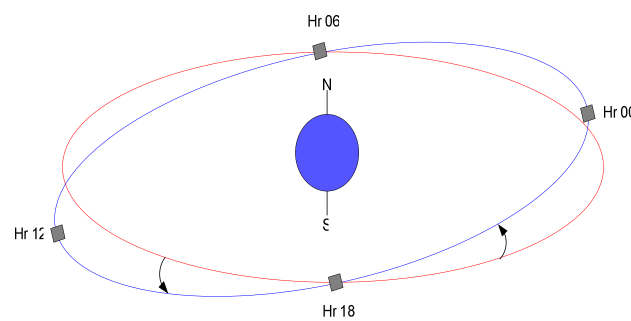

Figure 7: Satellite orbit view of Earth

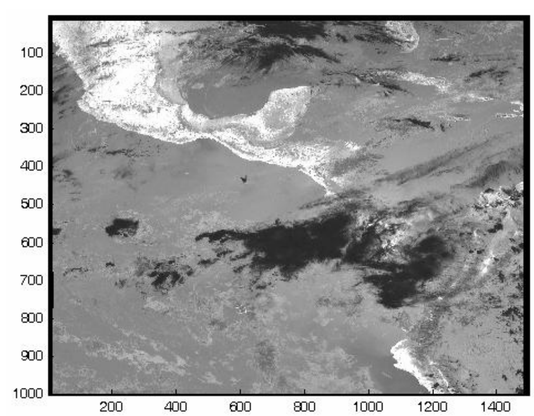

Figure 8: Original GOES image

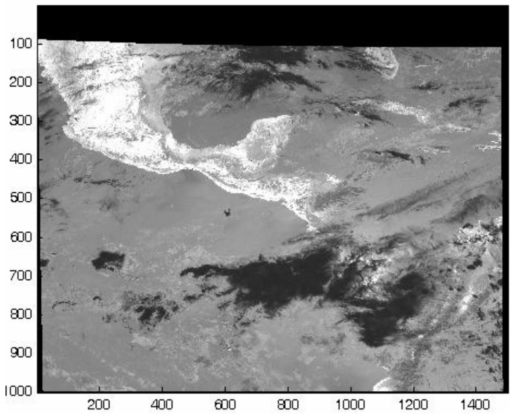

Figure 9: Simulated image at hour 00 and 4° inclination angle

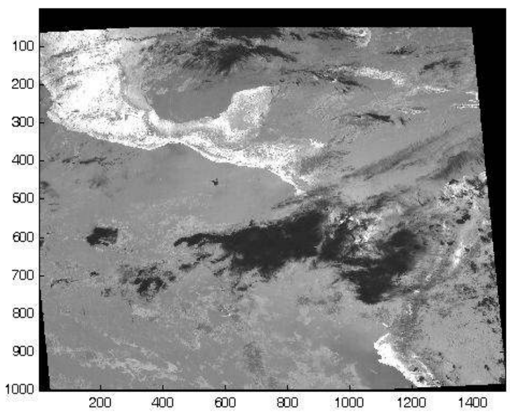

Figure 10: Simulated image at hour 06 and 4° inclination angle

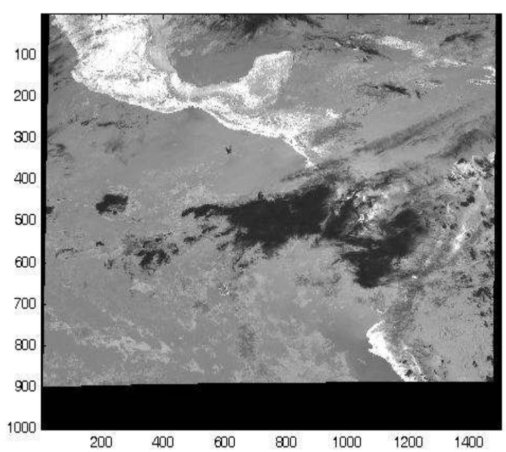

Figure 11: Simulated image at hour 12 and 4° inclination angle

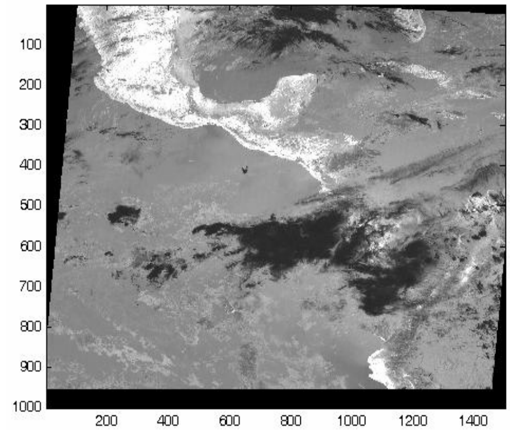

Figure 12: Simulated image at hour 18 and 4° inclination angle

VI. CONCLUSIONS

In this paper, we have investigated the implementation of Image Motion Compensation (IMC) on the ground through resampling with the objective to provide the same level of Image Navigation and Registration (INR) performance that is achieved with on-board IMC. Resampling affects the data in ways that depend on scene content and the resampling kernels in use. We have suggested different kernels depending on the needs of the user community.

ACKNOWLEDMENT

Support for this work was provided by COMMITS NEXTGEN NOAA Instrument Processing Engineering Support (IPES) Task.

REFERENCES

[1] Modernized Sensor Processing System (MSPS) User's Manual, GOES IJK/LMN Operations Ground Equipment (OGE), Operations and Maintenance Manuals DRL 504-06, Part 11 of 22, April 20, 2004

[2] Modernized Sensor Processing System (MSPS) Software Maintenance Manual, GOES IJK/LMN Operations Ground Equipment (OGE), Operations and Maintenance Manuals DRL 504-06, Part 17 of 22, April 20, 2004

[3] Modernized Sensor Processing System (MSPS) Hardware Operation and Maintenance Manual, GOES IJK/LMN Operations Ground Equipment (OGE), Revision 1, October 2005

[4] GOES Operations Ground Equipment (OGE) Interface Specification, DRL 504-01, Part 1, Revision 2, October 2006

[5] Blancke, B., J. Carr, E. Lairy, F. Pomport, B. Pourcelot, "*The Aerospatiale Meteosat Image Processing System (AMIPS)*", First International Symposium on Scientific Imagery and Image Processing, L'Association Aéronautique et Astronautique de France, April 1995

[6] Blancke, B., J. Carr, F. Pomport, D. Rombaut, B. Pourcelot and M. Mangolini, "*The MSG Image Quality Ground Support Equipment*", 1997 Meteorological Satellite Data Users' Conference, EUMETSAT, Brussels, Belgium, September 1997

[7] Carr, J., "Data Processing and Reprocessing" in *Manual of Remote Sensing*, F.C. Billingsley (ed.), American Society of Photogrammetry, Second Edition, 1983

[8] Carr, J. and D. Rombaut *"Optimal Deconvolution and Resampling*", First International Symposium on Scientific Imagery and Image Processing, L' Association Aeronautique et Astronautique de France, April 1995