Operational Pass Processing of Landsat TM and SPOT HRV Imagery within the Canadian CEODesk Processor

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ABSTRACT: This paper describes CEODesk, an innovative system for pass processing Landsat TM and SPOT HRV images within a central data archive. The system enables the turnaround time for geometrically corrected products to be reduced to as low as 12 hours within a distributed product generation environment. CEODesk generates precision geometric models over the entire pass of satellite imagery, extending previous pass processing algorithms to include modelling of multiple SPOT HRV segments. As part of the system development, the pass processing algorithms were tested on a sample dataset. The results of this assessment are presented here.

1. INTRODUCTION

A major impediment to the effective exploitation of Landsat TM and SPOT HRV imagery has been the inability to reliably deliver high quality, geometrically and radiometrically accurate products to the end user in a timely manner. With the expansion of the Internet, and the increased availability of raw satellite data, the data delivery bottleneck is quickly being eliminated. However, the problem remains how to turn this raw data into the quantitatively accurate image products desired for end users' applications. Geometric accuracy is most problematic as most users have neither the ground control points (GCPs) to precisely geolocate their products, nor ready access to the software to perform the geolocation and resampling. The question arises, "Is it possible for the central archive to take responsibility for generating and distributing high quality geometric models in a timely manner, thus relieving the desktop user from this burden?"

This paper discusses CEODesk (Canadian Earth Observation Desktop Processor), an innovative solution being developed by the Canada Centre for Remote Sensing to facilitate distributed precision geocoding on the end users' desktop. CEODesk will automatically construct precision geometric models at the central data archive over the full pass of satellite data. These geometric models are packaged with the raw data sent to the desktop. Simple desktop geocorrection software can then use these raw data products and produce precisely geolocated products without requiring user-supplied GCPs.

The idea of centralizing geometric processing has many advantages:

- the user is relieved from the burden of acquiring, marking, and maintaining a database of GCPs;
- the user can exploit desktop geocorrection software to produce all levels of image products up to orthoimages. This will enable a much broader range of novice users to have access to remote sensing imagery;
- the central archive can construct a precise geolocation model over the full pass of satellite data. This results in:
  - consistent geolocation models over the entire pass;
  - reduced need for GCPs in the central archive (e.g. far fewer GCPs per scene than traditional geocorrection techniques);
  - precision products over areas of no control (or where GCPs are obscured by features such as clouds or snow).

In addition, the CEODesk enables end users rapid access to precision geocorrected products within a distributed product generation system architecture.

In the sections which follow, we describe the overall design and context for the CEODesk system. We then present the core algorithm in the system, a new multi-segment pass processing algorithm. The algorithm is assessed on a sample set of Landsat and SPOT passes. As will be seen, excellent results were achieved for the Landsat datasets. The SPOT results, while preliminary in nature, also look promising.

2. CEODESK SYSTEM ARCHITECTURE

The Canada Centre for Remote Sensing (CCRS) is responsible for the acquisition, archiving, cataloguing, retrieval and distribution of raw satellite downlink data and auxiliary information for earth observation sensors over Canada. As part of Canada's Long Term Space Plan, CCRS has undertaken a suite of initiatives to help promote a new era of remote sensing in Canada that is focussed on rapid service to clients. These initiatives are described below.

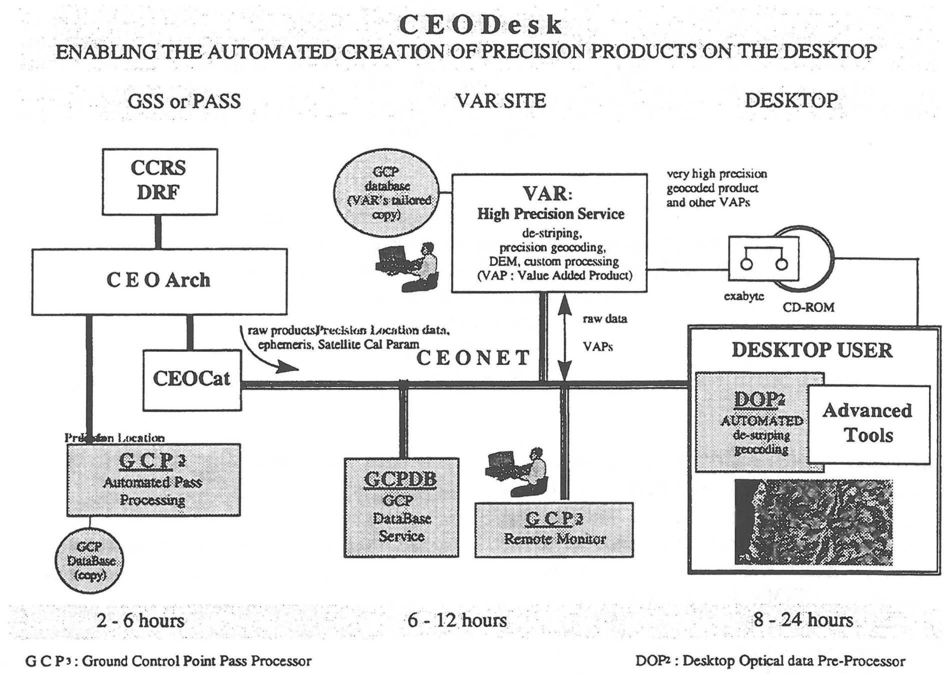

Figure 1: CEODesk System and Operational Context.

The Canadian Earth Observation Desktop processor (CEODesk) will enable the user to directly produce geometrically and radiometrically corrected optical satellite image products from raw image data. On-line ordering and delivery of raw data to the client's desktop will be accomplished through the CCRS Earth Observation Catalogue system (CEOCat), which is part of the Canadian Earth Observation Network (CEONet). The Canadian Earth Observation Archive (CEOArch) will make satellite data received at the CCRS data reception facilities readily available for rapid electronic delivery. The target is to reduce to 12 hours the time taken from the downlink of raw optical data to the production of the refined product by the client's desktop system.

Figure 1 illustrates the overall system architecture and operational context for CEODesk. The system is partitioned into two components: a Ground Control Point Pass Processor (GCP^3), and a Desktop Optical Precision Processor (DOP^2). GCP^3 resides within the ground station, and is responsible for generating the geometric correction models for the entire pass. DOP^2 resides on the user's desktop, creating geometrically and radiometrically corrected products in a highly automated fashion for direct use by the desktop user or as input to the user's advanced analysis software. Geometric models are passed from GCP^3 to DOP^2 by means of a set of supplementary data files.

MacDonald Dettwiler and Associates (MDA) of Richmond, British Columbia have been awarded the contract for the first phase of the development of the prototype CEODesk. MDA will deliver a GCP^3 system which can exploit an entire pass of downlinked data to calculate the geometric correction information needed by the DOP^2 image correction software. The prototype for SPOT HRV and LANDSAT TM data is due in the summer of 1998. CCRS will develop the database of the GCPs that are essential to the operation of the GCP^3.

This paper focusses on the algorithmic aspects of the GCP^3 system, in particular the pass processing algorithm. The following sections describe the algorithm, and present the results of testing the prototype GCP^3.

3. PASS PROCESSING ALGORITHM

A key challenge in constructing GCP^3 has been the development of a reliable pass processing algorithm. Pass processing of Landsat TM and SPOT HRV has been demonstrated previously (e.g. Sharpe 1988, Sharpe 1989), and the capability has been delivered in operational processing systems such as the National Landsat Archive Production System (NLAPS) built by MacDonald Dettwiler for the USGS Eros Data Centre (EDC). CEODesk adds a number of new features.

The core idea behind pass processing is the construction of a unified geometric model. All orbit and attitude data contained in the downlink are extracted and used to construct a coherent systematic model of the spacecraft over the pass. This systematic model results in a geolocation model accurate to within 2 kilometres.

Using this model as a starting point, GCPs are marked in cloud-free areas throughout the pass. The GCPs are added to a filter to update the systematic estimates of the satellite position and attitude over the pass. The filter typically models uncertainties in both position and attitude. The result is a consistent satellite model over the whole pass including areas where no control is available. Previous results (Sharpe 1988) have shown that sub-pixel accuracy is possible over a full pass of Landsat TM imagery and a single SPOT HRV segment if suitable control is available.

GCP^3's operational environment presents a number of new algorithmic challenges:

- The system must be capable of operating in a fully automated environment at the central archive. All GCP marking and precision spacecraft modelling algorithms must be automated with no operator interaction. This impacts the overall robustness of the image matching process and drives the complexity of the blunder detection algorithms;
- The system must be capable of simultaneously modelling both HRV cameras over multi-segment SPOT imagery (e.g. passes of SPOT imagery in which the HRV off-nadir looking mirror is changed). Previous work has been limited to the modelling of a single HRV camera over a single segment. To handle multi-camera, multi-segment imagery, the relative alignment between the cameras and between mirror movements must be correctly modelled. These may be affected by the thermal stability of the optical bench, and by the ability of the mirror to precisely reposition itself (to sub-pixel accuracy) after a change in look angle;
- The system must have access to a reliable database of accurate GCPs (and associated image chips) over the pass. This is a particular challenge over the Canadian landscape which has a vast extent of sparsely populated land-mass (and thus lacks stable man-made features) north of 55 degrees latitude, and has extensive snowfall coverage in the fall, winter and spring seasons.

Each of these issues is explored in further detail below.

3.1 Automated GCP Marking

The automated GCP marking algorithm is critical to the operational success of GCP^3. No operator is available to manually assist in the control collection process, thus the algorithm must be robust, and designed to operate in a batch mode. The algorithm must automatically identify candidate GCPs, mark them in the imagery, then update the geometric models.

To select candidate GCPs, the algorithm first calculates the approximate extent of the pass of imagery, and queries the GCP database for all GCPs within the footprint of the sensor. To improve throughput, cloud cover estimates generated during the image cataloguing process are used to eliminate GCPs in regions with heavy cloud cover. Once this filtered list of GCPs is available, automatic GCP identification proceeds.

The GCP identification algorithm uses standard image correlation techniques. For each GCP, an associated image chip is selected from the database, and correlated against the raw image using a configurable correlation algorithm. As GCPs are marked, statistical tests are performed to identify and remove blunders (mis-matched GCPs) before they are added to the model. This is a critical step in ensuring the success of a fully automated algorithm.

After blunder detection, the remaining GCPs are incorporated into the model. The filter incorporates all a priori information on the accuracy of the systematic spacecraft model. The result is a consistent, accurate spacecraft model over the complete pass of imagery, including areas of the segment where no control was available.

3.2 SPOT HRV Multi-Segment Modelling

Constructing a single geometric model for a full pass of SPOT HRV imagery represents a key algorithmic challenge for GCP^3. While the configuration of Landsat TM is static over a pass, the two HRV cameras carried on the SPOT satellites are programmable. A SPOT pass is decomposed into a series of independent segments with varying off-nadir mirror angles and sensor gain modes within each segment. This can introduce errors in the geometric models due to:

- changes in the relative alignment between the two HRV instruments;
- changes in the relative alignment between the Pan and XS cameras;
- uncertainty in the "repositioning" of the off-nadir pointing mirror.

Analysis of several years of SPOT data indicates that 50% of Canadian passes contain more than one segment, with over 15% of the passes containing three or more segments. Thus multi-segment HRV passes represent a real operational concern.

Considering the underlying cause of the multi-segment distortions, the residual per-segment geometric errors are expected to take the form of a constant bias over a segment. To handle this, the existing pass processing models have been extended to refine the spacecraft attitude separately in each segment. An additional roll, pitch, and yaw uncertainty term is added to the model at each segment boundary.

To implement this, the pass processing algorithm described above has been augmented to refine all SPOT segments from a single pass simultaneously. As before, correction parameters (roll, pitch, yaw, and satellite position) are applied to the entire pass across all segments. Additionally, each segment has its own set of attitude corrections. The filter simultaneously estimates all parameters so that a single optimal solution is determined.

3.3 Compilation of Accurate Control

The success of any automatic GCP marking scheme relies on the availability of a sufficient set of high quality GCPs over the area of interest. Since the goal of CEODesk is to obtain pixel level geometric accuracies over the whole Canadian land-mass, a GCP database with sufficient accuracy and density must be compiled.

To estimate the density of the control point database, the cloud cover characteristics for Landsat TM passes were determined by performing a statistical analysis of the cloud cover data in the CCRS satellite catalogue. The results, shown in Table 1, illustrate the extent of the cloud cover problem in Canada. Fully 25% of Canadian passes contain no cloud-free quadrants. Based on this analysis, and the goal of marking control in 10 quadrants of the pass, we estimate that a control density of 2 GCPs per Landsat TM quadrant is required to process 80% of the passes. This corresponds to approximately 6400 control points over the Canadian land-mass.

Having determined the required density, a suitable source of GCPs must be found. To achieve pixel level accuracies for 10 metre SPOT Pan imagery, a source of control with better than 10 metre accuracy is required. The problem is further complicated by:

- datum shifts: over a 3000 kilometre pass, distortions introduced by different datums (e.g. NAD27 and NAD83) become significant at the 10 metre level;
- map quality: often only 1:250,000 scale maps are available in parts of the Canadian north;
- identifiable features: the bulk of Canada's population lives within 200 kilometres of the southern border, thus there is a lack of good stable features such as road intersections for much of the area.

During initial system tests, an existing satellite GCP database was exploited. While providing good qualitative results, the control was observed to have underlying problems. Much of it had been generated in the early days of Landsat MSS, thus was unsuitable for use with higher resolution sensors. It was concluded that this control database could not be used for quantitative system assessment.

To acquire more accurate GCPs over a test corridor defined by Landsat tracks 46 and 47 over Canada, two techniques were used:

- Below 60 degrees north, 1:20,000 maps from the recently compiled British Columbia TRIM program were used. GCPs were identified in the Landsat passes, then their coordinates digitized from the maps;
- Above 60 degrees north, available aerial photography, providing almost complete coverage of the Canadian north, was exploited. Promising areas were identified in Landsat passes. The corresponding air photos over the areas were digitized, remapped to the UTM grid (NAD83 datum), and GCPs identified in the resulting images.

The result of this process was a complete corridor of containing 127 GCPs with an estimated RMS accuracy of better than 10 metres.

4. PRELIMINARY PROCESSING RESULTS

To test the performance of CEODesk, the system was assessed on a dataset consisting of a corridor of imagery from Baffin Island in the North West Territories to the west coast of British Columbia (spanning approximately 10 minutes of satellite data). The dataset included three Landsat TM passes, and two SPOT HRV passes. Table 2 contains a summary of the datasets. Figure 2 provides a plot of the ground tracks of the TM and HRV_Test1 datasets, and the location of the high quality GCPs described in Section 3.3.

Table 1: Cloud-Cover Analysis for 1020 Landsat TM Passes in 1996.

	Percentage Passes With Specified Cloud Cover			
Percent Cloudy	>1 quadrant	> 10 quadrants	> 20 quadrants	> 30 quadrants
0%	75%	34%	14%	5%
<= 20%	95%	79%	51%	29%
<= 40%	96%	87%	67%	38%
<= 60%	98%	93%	83%	66%

Table 2: Description Of The Landsat TM and SPOT HRV Test Datasets.

Dataset	Satellite/Sensor	Acquisition Date	Duration (min:sec)	# Segments
TM_Test1	Landsat-5 TM	11-May-1997	9:17	n/a
TM_Test2	Landsat-5 TM	22-July-1994	9:31	n/a
TM_Test3	Landsat-5 TM	21-Sept-1993	8:30	n/a
HRV_Test1	SPOT 2 HRV1/2	17-June-1993	6:41	8
HRV_Test2	SPOT2 HRV 1/2	07-Sept-1993	6:32	8

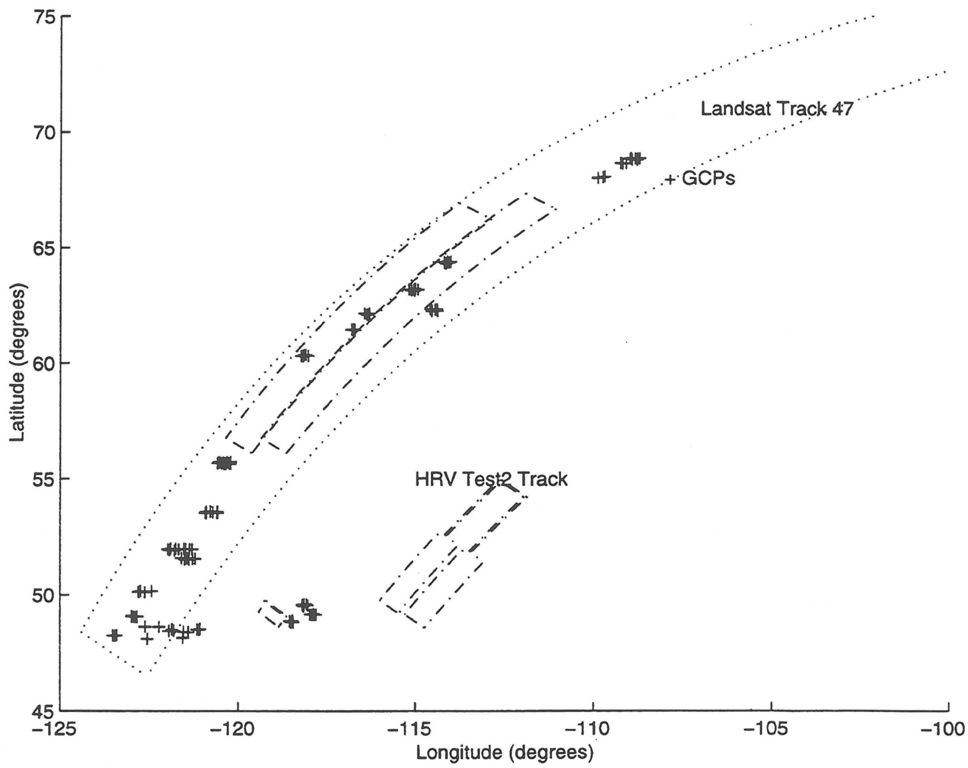

Figure 2: Plot Of The Distribution Of The Test Datasets And Control.

This section presents the results for both Landsat TM, and SPOT HRV. Sufficient high quality GCPs were available to perform detailed quantitative tests on the path 47 Landsat TM datasets. To date we have yet to acquire sufficient high quality control to thoroughly assess the multi-segment SPOT models. As Figure 2 shows, whole segments of HRV imagery exist without any suitable GCPs. Therefore, the SPOT results presented are preliminary in nature.

4.1 Landsat TM Test Results

The CEODesk system was assessed on the three Landsat TM datasets described above. In each case, the pass of data was processed automatically using the GCP database described in Section 3.3 Table 3 presents the results of these test cases. Figure 3 provides an example plot of the residuals at each control point for one of the test cases, TM_Test1.

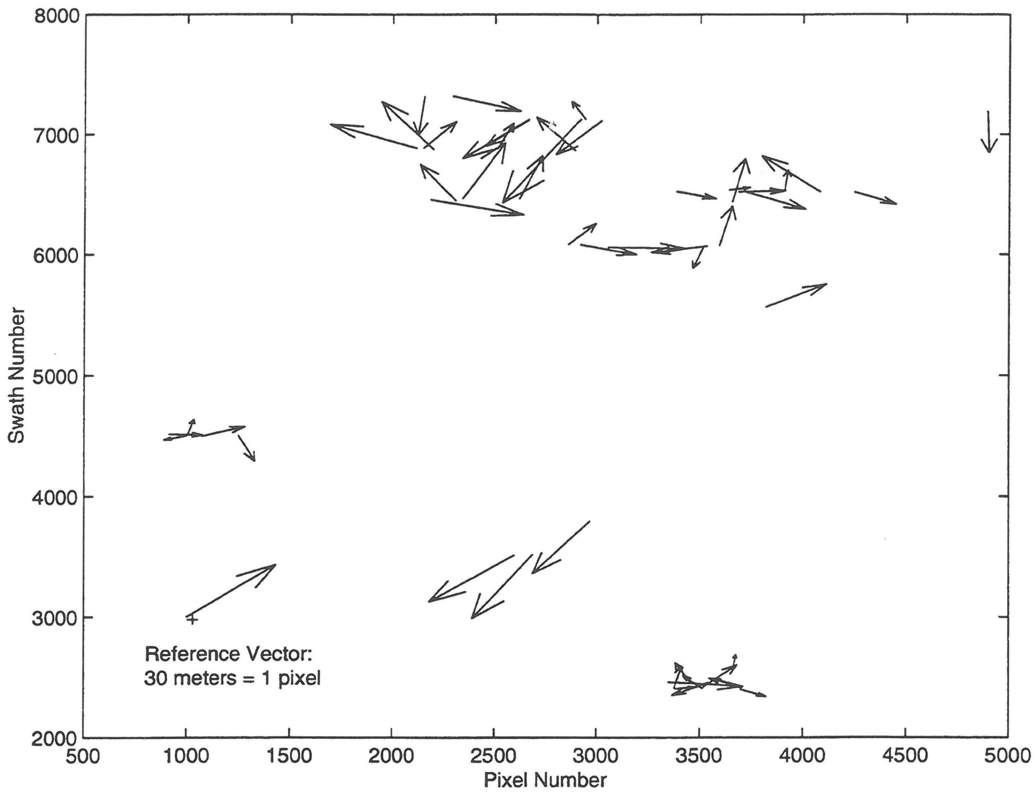

Figure 3: Ground Control Point Residuals for Test Case TM_Test1.

Table 3: Results Of Landsat TM Pass Processing Tests.

Dataset	# GCPs	Along Track Residual (metres)	Across Track Residual (metres)	Combined Error (metres)
TM_Test1	56	19.6	25.6	32.2
TM_Test2	35	18.7	15.8	24.5
TM_Test3	82	17.6	19.8	26.5

In all three test cases, the system was able to automatically identify and mark a complete set of GCPs well distributed over the pass. The residuals errors at the GCPs are small, indicating that position and attitude errors over the pass are adequately modelled by low order corrections to position and attitude. Figure 3 also supports this conclusion as there are no significant systematic trends in the error residuals after the pass processing model has been run.

These test results suggest CEODesk is capable of generating geolocation models for full passes of TM imagery with pixel-level accuracy.

4.2 SPOT HRV Test Results

To assess the performance of the multi-segment extension to the pass processing algorithm, two multi-segment SPOT passes were analyzed. As mentioned earlier, insufficient high quality GCPs are available over the SPOT ground tracks, thus the passes were refined with GCPs from the lower quality GCP database described above. As such, only qualitative conclusions can be drawn from the tests.

The SPOT test trails proceeded as follows. GCPs were marked in all segments of each pass, and three modelling scenarios assessed. In the initial scenario, each segment was modelled separately with a local correction for satellite position, attitude bias, and attitude rate. In the second scenario, all segments were modelled globally using a traditional pass model with no per-segment correction terms. Finally, the third scenario modelled all segments with a single pass model consisting of a global low order correction for satellite position and attitude, and a per-segment attitude correction. The results of these tests are provided in Table 4.

Table 4: Results of SPOT HRV Single Segment and Pass Processing Tests.

Satellite/ Sensor	Segment Number	Off-Nadir Angle (deg.)	Segment Duration (minutes :seconds)	Number of GCPs Marked	Single Segment Model Residuals (metres)	Traditional Full Pass Model Residuals (metres)	Multi-Segment Full Pass Model Residuals (metres)
HRV_Test1							
H1Pan	1A	25.4	1:13	10	28.1	77.4	56.1
H1Pan	2A	23.6	2:47	43	26.2	45.3	27.6
H1Pan	3A	8.0	0:57	10	27.1	37.5	27.9
H1XS	4A	1.7	1:44	0	N/A	N/A	N/A
H2Pan	1B	15.4	1:13	12	16.3	24.1	19.5
H2Pan	2B	21.4	2:47	34	26.1	48.9	29.5
H2Pan	3B	0.4	0:57	34	30.4	36.1	34.1
H2XS	4B	21.4	1:44	11	20.0	30.4	26.9
RMS Totals					26.4	44.5	31.6
HRV_Test2							
H1Pan	1A	12.4	3:15	19	21.0	59.6	22.3
H1Pan	1B	22.4	0:46	20	20.0	45.3	25.2
H1Pan	1C	21.2	1:00	30	24.7	34.0	27.0
H1XS	1D	6.8	1:31	8	11.2	40.5	14.7
H2Pan	2A	8.5	3:15	32	25.4	42.4	27.0
H2Pan	2B	22.1	0:46	23	24.7	42.7	27.7
H2Pan	2C	24.5	1:00	25	27.5	56.9	35.0
H2XS	2D	7.1	1:31	10	21.9	63.5	38.1
RMS Totals					23.7	47.5	28.0

Analyzing the results for the single segment models, we infer that the quality of the control points over each segment is roughly 25m RMS. This observation is based on the previously described issues with these GCPs, and the fact that previous work [Sharpe 89] has shown that sub-pixel accuracy (6 metres) is possible using pass processing techniques within a single segment when accurate control is available.

Turning to the multi-segment models, we observe that modelling all SPOT segments with a single pass model (no per-segment biases) results in a significant degradation in the overall accuracy of the models. RMS residuals of the GCPs over the pass go from about 25 metres to about 45 metres. However, when the per segment attitude corrections are introduced into the model, error residuals are reduced to a level close to those observed when modelling the segments separately. The one outlier (HRV_Test1/1A) exhibits much poorer results. This is likely due to the quality of the control, and not a fundamental flaw with the algorithm.

These initial results support the conclusion that the per-segment attitude correction correctly mimics the operational characteristics of the HRV sensor. Further, they suggest it is possible to correct a multi-segment SPOT pass with control in each segment using a unified, low-order model and achieve accuracy results approaching those of single-segment modelling.

5. CONCLUSIONS

CEODesk provides an innovative mechanism to support the timely delivery of accurately geocorrected products to the end user in a distributed processing environment. Within this architecture, GCP^3 provides the central pass processing engine responsible for the geometric models.

Assessment of GCP^3 on a corridor of Landsat TM imagery has shown that the system is capable of generating geometric models with errors on the order of one pixel over a complete Canadian pass. While more assessment of the system is required on a larger number of passes (including passes with more cloud cover), this is a very promising result.

Initial assessment of the system on two multi-segment SPOT HRV passes indicates that the proposed extensions to the traditional single segment pass processing algorithms perform well. A global pass model augmented by per-segment attitude corrections effectively characterizes the performance of the HRV sensors over a full pass.

There remain a number of unanswered questions. The SPOT test cases need to be rerun when more accurate GCPs have been compiled using the techniques described in Section 3.3. Such tests will aid in answering the following questions:

- what accuracy can be achieved with the proposed algorithm over a full SPOT pass?
- how stable is the relative inter- and intra-HRV camera alignments both within a pass, and between passes?
- how well do the SPOT results extrapolate both within a segment and between segments?

These questions will be investigated further in the coming months.

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