

INTERIOR ORIENTATION OF SPOT IMAGERY

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Abstract

The interior orientation of the SPOT HRV instrument differs from a photographic camera mainly by its 1-dimensional nature and discrete detector positions. The nonlinearities and discontinuities in the detector positions are of special concern. A method is here developed for the calibration of detector positions with accuracies better than $1\mu\text{m}$. The calibration was applied to the panchromatic sensors in SPOT-1. It proved to have a significant influence on the quality of DTM's produced from SPOT stereopairs, where systematic errors up to 10m can be eliminated.

Key Words: Calibration, DTM, Image Quality, Sensor, SPOT

INTRODUCTION

The HRV instrument is similar to a camera in some respects. There is an optical assembly which forms the optical image in the focal plane (figure 1). The main difference is that the optical image is not registered by the continuous 2-dimensional media of a photograph, but by 1-dimensional CCD arrays with discrete detector positions (figure 2).

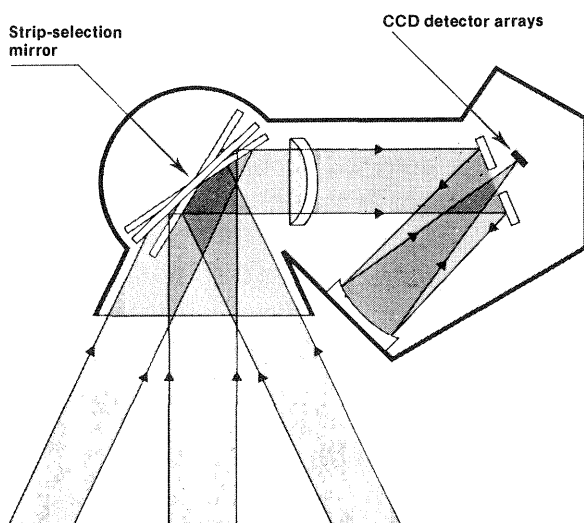


Fig. 1. Cross-section of the HRV instrument.

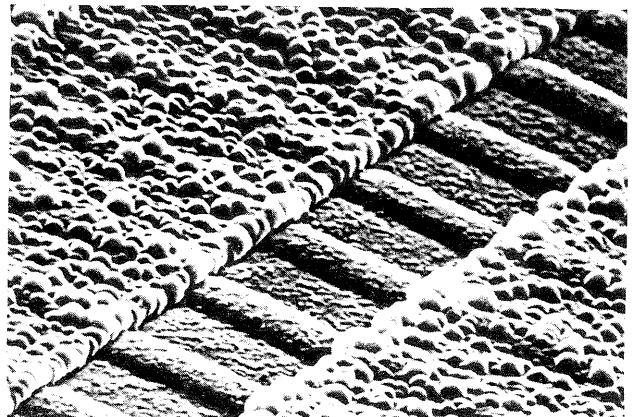


Fig. 2. Enlargement of a small portion of a CCD array, showing about seven individual detectors (Courtesy of SODERN, contractor for the SPOT camera detection system).

The imaging is based on the "pushbroom" technique, where one image line is registered simultaneously by 6000 detectors in CCD arrays. The P line thus comprises 6000 pixels, while the XS line only comprises 3000 pixels because it utilizes two elementary detectors per detector array for each spectral band is formed by four separate 1728-point CCD arrays, using 1500 detectors from each. The nominal inter-

detector distance is $13 \mu\text{m}$. The four CCD arrays can not be placed edge-to-edge without serious discontinuities in inter-detector distance at the array joints. To overcome this problem, the four CCD arrays were glued on the faces of an optical divider, called DIVIOLI (figure 3). Here, the positions of the CCD arrays were adjusted, to form a continuous virtual line of high accuracy.

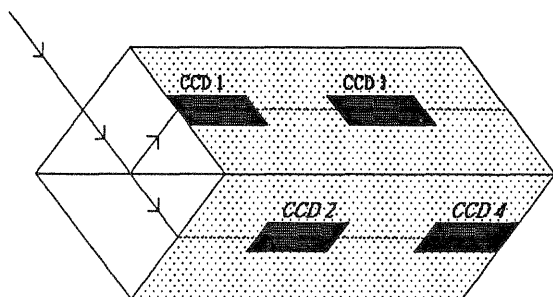


FIG. 3. The DIVIOLI.

The small field of view (4.13°) reduce the magnitude of many of the distortions due to the optics. Instead, we get a new type of distortion due to errors in the positions of the individual detectors in the arrays, and in the relative position of separate CCD arrays. If we treat the remaining optical distortions as part of the detector position errors, then the interior orientation of an HRV instrument can be described by four elements:

1. Principal distance.
2. Position of the principal point.
3. Radial (along-line) errors in the detector positions.
4. Tangential (across-line) errors in the detector positions.

In this paper, methods for the calibration of these elements will be discussed and developed, and applied to the SPOT-1 satellite.

PRINCIPAL DISTANCE

The preflight nominal principal distance for SPOT-1 were:

1082 mm	HRV1
1082 mm	HRV2

(Midan, 1986). This may, however, have changed, e.g. due to inflight refocusing of the instruments. The new values are indirectly given on the image data CCT as the viewing directions of the first and the last detectors in the arrays, together with the nominal inter detector distance of $13 \mu\text{m}$. The new postlaunch nominal values thus become:

1084.49 mm	HRV1
1084.12 mm	HRV2

Inflight calibration of the principal distance is very difficult. A small error in the principal distance is absorbed as a change in orbit radius in the modeling of exterior orientation. In the specifications, the orbit radius should be within 500 m from the predicted value. By experience, we also know that the change in radius almost never exceeds 500 m in the exterior orientation. This indicates that the error in principal distance is small enough to be confused by the normal variation in orbit radius. The only way to determine a deviation from the nominal principal distance would be by means of statistics from a large series of results from exterior orientations, looking for a bias in the average change in orbit radius.

Finding a principal distance deviation of this small size is, however, of little practical interest. The potential problem of an error in principal distance is that it causes an elevation dependent scale error. A 500 m change in orbital radius compensates a 0.65 mm change in principal distance. If the control points in exterior orientation is taken at the sea level, the scale will be correct at sea level. At 5000 m level, the 0.65 mm principal distance error would then cause a scale error of only 3.5 ppm, corresponding to 0.2 m over the entire width of a SPOT scene.

While the absolute size of the principal distance is given with sufficient accuracy by the nominal values, the relative principal distance between the two instruments is needed with higher accuracy and has to be calibrated, as it is of importance also in bundle adjustment of SPOT scenes. The problem arises if both instruments are used simultaneously to register scenes for the adjustment. The exterior orientation can then only compensate the error in principal distance in one of the instruments. If there is a different error in the second instrument, it will cause an error in relative scale between the scenes. A 0.65 mm difference would now cause a 600 ppm scale error, corresponding to 36 m over the width of a SPOT scene.

The relative principal distance was calibrated by relative orientation of a pair of overlapping panchromatic SPOT-1 scenes acquired simultaneously by HRV1 and HRV2. The relative orientation was performed according to the method described in Westin (1990), but with an extra parameter added to account for a difference in focal length. The final principal distance values adopted after relative calibration are:

1084.49 mm	HRV1
1084.20 mm	HRV2

PRINCIPAL POINT

The calibration of the position of the principal point is difficult for the same reasons as for the principal distance. A small error in the position of the principal point is absorbed in the exterior orientation primarily as a deviation in roll angle. The AOCS is designed to keep the attitude angles within 0.15° , and by experience we know that these are not exceeded in the exterior orientation. This indicates that the error in the position of the principal point is small enough to be confused with the normal variation in the roll angle, i.e. that it is less than 200 pixels. Similar arguments as for the principal distance also reveal that errors of this magnitude is of little practical importance, because the distortions induced are insignificant. The

relative difference between instruments is, in this case, not of great importance either, as there is a corresponding uncertainty in the relative roll angles between instruments, which always has to be modeled in the exterior orientation. The nominal positions of the principal points, i.e. the mid-points of the detector lines, were thus adopted for the rest of this study.

DETECTOR POSITIONS

Measurements

As the detector arrays are always in the same position relative to the optical system, it is impossible to distinguish errors due to optical distortion from errors in the detector positions. We will in the following refer to the combined effect of these errors as detector position errors, remembering that part of it may be caused by optical distortion. The accuracy we are aiming for in the calibration is around 1/10th of a pixel, as larger errors will have a noticeable effect in stereo processing of SPOT imagery.

It is difficult to adopt standard inflight calibration techniques for aerial cameras to the SPOT case. To construct a test field with three-dimensional targets would be unrealistic, due to the large size of a SPOT scene, and to the large size of targets necessary to be visible. Multi-frame analytical calibration with ordinary control points would be a possibility if we could express the errors in a functional form with relatively few parameters. There is, however, no guarantee that the CCD arrays are manufactured with a high enough accuracy to exclude the possibility for irregular errors larger than 1/10th of a pixel along the arrays. Depending on the unknown correlation between these errors, it requires that we introduce from several hundreds to several thousands of parameters in the analytical calibration, which makes it an unrealistic calibration method for SPOT.

In Westin (1992), a new calibration method is

developed, which utilizes the possibility to simultaneously image the same area on ground by the two instruments on SPOT. An image pair acquired in this way, can be thought of as a stereo pair with a base-to-height ratio of zero. If there still are parallaxes present in the image pair, these must be functions of the detector position errors in the instruments.

After absolute orientation and resampling (Westin, 1990), the parallaxes were measured by an automatic matching method for digital SPOT stereo pairs (Rosenholm 1987). The procedure is very much the same as for normal stereo processing of SPOT stereo pairs, but parallaxes were measured not only in the along-line direction, but also in the across-line direction. The parallaxes were then averaged along the detectors ground track, to give estimates of the parallaxes as functions of the detector numbers in the CCD arrays.

Three image pairs with different overlaps were measured. Examples of the results are shown in figure 4 for differences in the along-line direction, and in figure 5 for across-line differences. The positions for CCD array joints are marked as vertical lines in the figures. The misalignments at the joints show up clearly, but it is also obvious that there are other detector position errors, within the separate arrays, which are contributing to the result. This can be seen by the non-linear behavior of differences between joints.

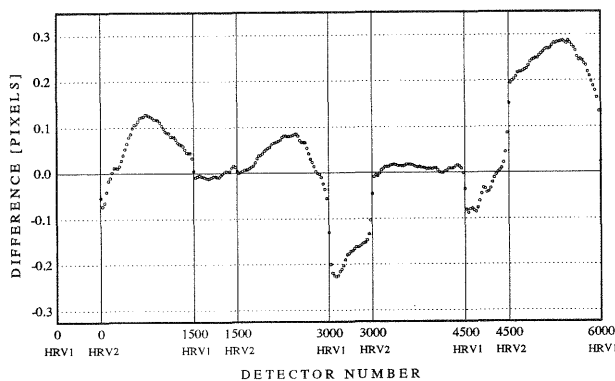


Fig. 4. Measured parallaxes in the along-line direction in the first image pair.

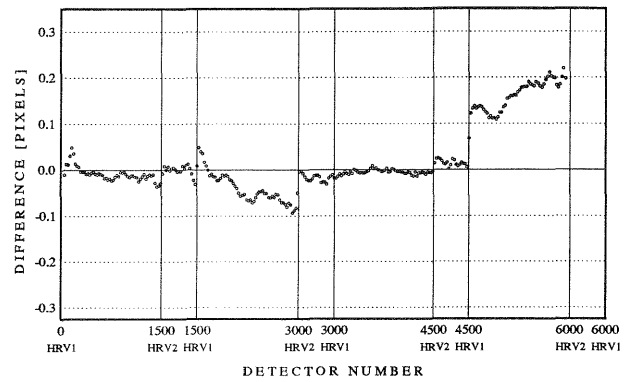


Fig. 5. Measured parallaxes in the across-line direction in the second image pair.

Adjustment

An adjustment procedure can be developed based on the very simple equations relating the parallax measurements to the detector position errors, i.e. the parallax at a point is the difference between the position errors in the two detectors imaging that point,

$$p(i) = e_{hrv1}(i) - e_{hrv2}(i + \Delta)$$

where i is the detector (or rather detector group) number, and Δ is the along-line displacement between the images in the pair.

It is easily recognized that measurements from one image pair is not sufficient to solve the unknown position errors. Two image pairs with different displacements will almost give as many observations as there are unknowns, but the system will still be underdetermined. With three or more image pairs the system will be overconstrained, but, more surprisingly, still underdetermined. This fact is investigated in detail in Westin (1992). There it is shown that, although there are infinitely many least squares solutions, the unique minimum-norm least-squares solution is the most probable alternative. The mathematical solution with a generalized inverse is there formulated, and a numerical method to solve the problem is outlined.

Calibration results

The calibration method was applied to three image pairs from the SPOT-1 panchromatic sensors. The computations gave results with a good least squares fit, the estimated standard deviations in the parameters were only around 0.02 pixels, or $0.26 \mu\text{m}$. The position errors as functions of detector number are presented as diagrams in figures 6, 7, 8 and 9.

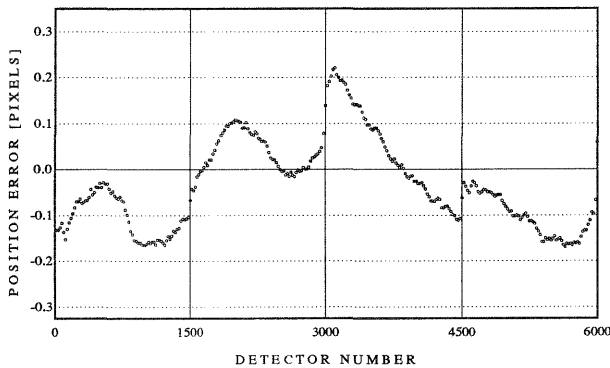


Fig. 6. Along-line position errors in HRV1.

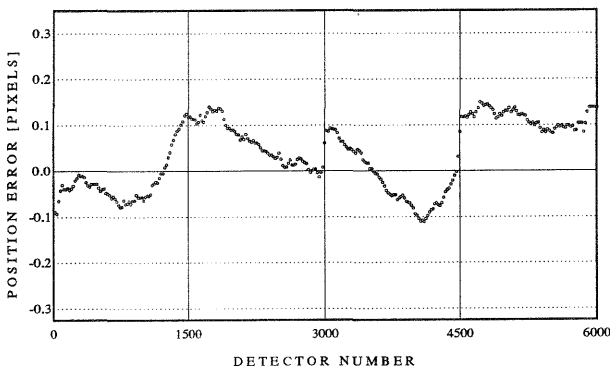


Fig. 7. Along-line position errors in HRV2.

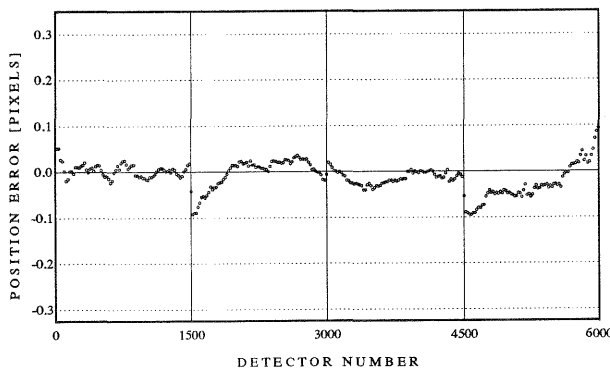


Fig. 8. Across-line position errors in HRV1.

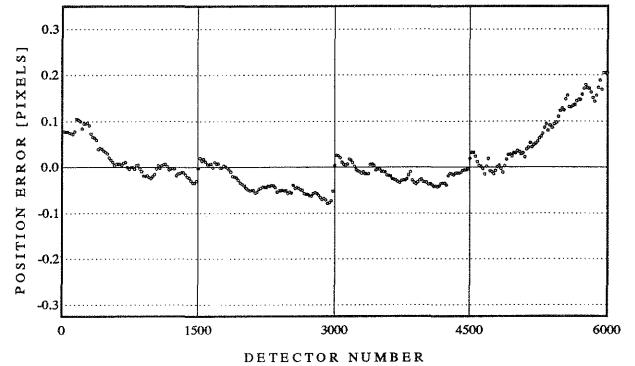


Fig. 9. Across-line position errors in HRV2.

The results reveal position errors large enough to have a significant effect on DEM calculations from SPOT stereo pairs. The along-line errors can introduce false parallaxes in the order of 0.4 pixels, which is much larger than the 0.15-0.20 pixel accuracy achievable in digital stereo matching (Rosenholm, 1988). It would correspond to a 10 m elevation error at a base-to-height ratio of 0.4.

Also the across-line offsets introduce errors in the DTM, at places where the dominant feature is oblique to the column direction. This may for example introduce different systematic errors in the elevation of a river, depending on its direction of course.

IMPROVEMENTS IN DEM COMPUTATIONS

The detailed calibration of detector position errors can be used to correct the imagery during resampling. This was implemented and tested in a real stereo processing case. Two digital elevation models were computed from the same SPOT stereo pair, one with images corrected for detector position errors, the other with uncorrected images. Both results were compared to a DEM compiled from aerial photography by the National Swedish Land Survey.

When comparing the result from the uncorrected image pair, regional differences (from 4 m to -4 m) were found which agreed

very well with those predicted from the calibrated detector position errors (figure 10). The result from the corrected image stereo pair displayed only random differences. (From both result were first removed a constant bias of 5 m, which is supposed to be caused to the limited accuracy in the relative orientation of the stereo pair.)

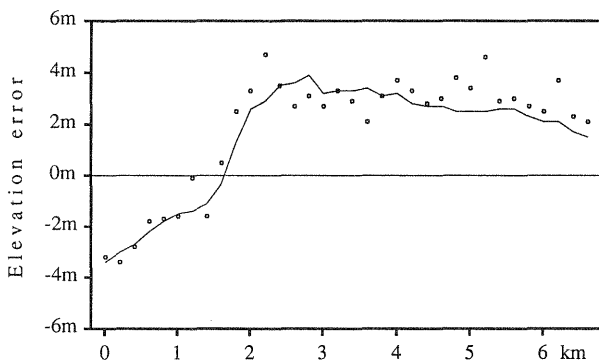


Fig. 10. Difference between the computed DTM (without detector position corrections) and the reference DTM as a function of ground distance along the array. The solid line is the errors predicted from the result of the calibration.

CONCLUSIONS

If a "pushbroom" line-scanning satellite is equipped with two independent instruments, such as in the case of SPOT, a very accurate self-calibration of interior orientation become possible. A method was developed that uses simultaneously recorded overlapping images from the two sensors. Extracted information on differences between the images can be used to solve for the radial and tangential errors as a function of detector number.

Applying this method to the panchromatic sensors in the SPOT-1 satellite revealed significant errors that were large enough to introduce systematic errors when using SPOT images for DTM computations. The calibration result made it possible to correct SPOT imagery before stereo processing, thereby eliminating systematic errors in the computed elevations.

The use of this method is not restricted only to line scanners. It can be extended to other types of sensors, such as 2D-arrays or photographic cameras, provided there are at least two independent sensors capable of recording overlapping images in different configurations.

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