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Nuclear Instruments and Methods in Physics Research A 506 (2003) 92–100

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The RASNIK real-time relative alignment monitor for the CDF inner tracking detectors

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Received 27 November 2002; received in revised form 17 February 2003; accepted 24 February 2003

Abstract

We describe the design and operation of the RASNIK optical relative alignment system designed for and installed on the CDF inner tracking detectors. The system provides low-cost minute-by-minute alignment monitoring with submicron precision. To reduce ambiguities, we modified the original three-element RASNIK design to a two-element one. Since the RASNIKS are located within 10–40 cm of the beam line, the systems were built from low-mass and radiation-hard components and are operated in a mode which reduces damage from radiation. We describe the data-acquisition system, which has been running without interruption since before the CDF detector was rolled into its collision hall in March 2001. We evaluate what has been learned about sources of detector motion from almost 2 years of RASNIK data and discuss possible improvements to the system.

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PACS: 07.07.Df; 42.15.Eq; 29.40.G

Keywords: Sensors (optical); Optical system design; Tracking and position-sensitive detectors; RASNIK; Relative alignment

1. Introduction

A critical feature of the major upgrade of the CDF experiment [1] at Fermilab is its inner silicon trackers. These detectors provide the ability to reconstruct and trigger on clusters of charged tracks originating 100–1000 μm away from the primary interaction. Such detached vertices of charged particles, which may indicate the presence of a particle containing a b quark, are critical to the CDF physics goals: characterization of top quark production and decay; measurements of

heavy flavor mixing; CP violation and rare particle decays; searches for supersymmetric particles and, eventually, searches for the Higgs boson. However, the ability to resolve the separation between the detached vertex and primary interaction requires that the silicon trackers remain stable to approximately 10 μm .

While detector alignment can be accomplished with tracks taken over a long integration time, the RASNIK technique (Relative Alignment System of the Nikhef Institute) [2] offers a low-cost tool to observe motion on the time scale of seconds with sensitivity better than 1 μm . RASNIK systems are being developed for the Atlas [3] and CMS [4,5] experiments which are currently being installed at the Large Hadron Collider at CERN. These

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systems have already been installed in a running experiment—the CHORUS experiment at CERN used RASNIKS [6] to monitor the alignment of detectors used to track particles back into a photographic emulsion.

In Section 2 we describe the RASNIK principle and the modifications we made to specifically adapt it to CDF’s silicon inner tracker. In Sections 3 and 4 we describe the specific implementation at CDF and discuss the data. In Section 5 we discuss possible improvements to the system.

2. The two-element RASNIK

The original RASNIK principle is based on projecting the image of a finely detailed mask through a lens onto a small digital camera, as shown in Fig. 1a. The three components (mask, lens, camera) are mounted on separate detector subsystems and/or support structures. If any one of these three elements moves there will be a corresponding movement of the projected image on the camera. In this fashion, the system tracks the relative alignment of the pieces. A typical mask in such a system is a grid of black and white

squares of order $100\ \mu\text{m}$ size, photo-etched onto a thin quartz slide. As shown in Fig. 2, deviations from a perfect grid are coded into the pattern to remove large scale position ambiguities; it is therefore called a “coded mask”. The use of such a pattern provides great statistical power since there are hundreds of black/white transitions to measure in a given image.

For our application on the CDF trackers we removed one movement ambiguity by integrating the light source, coded mask and lens into a single “projector” piece. The asymmetry of the technique introduces magnification, so new masks using smaller $20.00 \pm 0.01\ \mu\text{m}$ squares were printed. The resultant two-element system is compared to the original three-element technique in Fig. 1b. Because the mask is coded, at least 10 squares (contiguously in both horizontal and vertical directions) must be visible to the camera in order to reconstruct the global position. Since the magnification changes for different projector–camera distances, “baselines”, we provided the projector with several slots for positioning the coded mask. Hence the magnification can be kept roughly constant, independent of the particular baseline, by a small change in the placement of the coded mask. Providing multiple locations for the mask also eliminates the need for a diffuser, allowing the use of a single LED and further

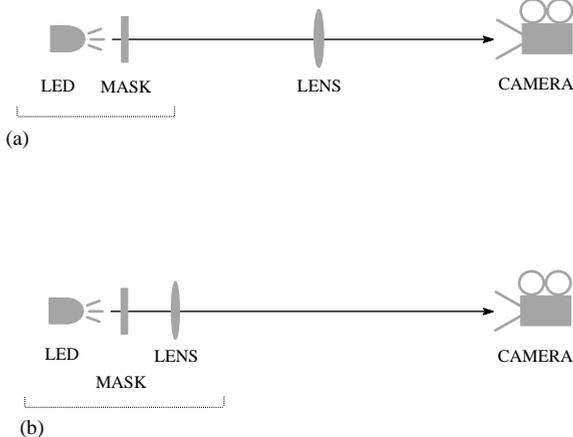


Fig. 1. The basic features of the RASNIK technique for the (a) original three-element system and (b) the two-element system developed for CDF. Incorporating the lens into the projector piece introduces system-specific magnification; this complicates position analysis, but eases installation and reduces ambiguity. Without this modification the installation of RASNIKS in the environment at CDF would not have been feasible.



Fig. 2. A typical image from the CMOS camera after capture by the frame grabber. Each small square is $20\ \mu\text{m}$ on each edge. The interrupts which encode the global position on the mask are visible as irregularities in the checkerboard pattern.

reducing the power consumption and mass of the piece. Since the depth of focus is typically of order 1 mm, the lens is mounted in a threaded barrel so that final focus can be achieved after both the projector and camera are glued in place. Fig. 3 shows a photograph of the actual projector and camera pieces used in CDF.

Because the elements are placed so close to the beam line they have to be low-mass and radiation-hard. The projector piece is made of thin polycarbonate, which provides ample rigidity for components of this small size. A projector in situ (with mask, lens, and LED installed) weighs approximately 20 g. A typical particle trajectory which traverses the piece corresponds to approximately 1% of a radiation length. Various optical materials were tested in the UC Davis cyclotron, exposing them to ~ 200 krad using a 63 MeV proton beam.¹ This roughly corresponds to the maximum integrated dose expected for a RASNIK mounted on the inner tracker (“SVX”) over the course of CDF’s Run IIa. As a result of these tests we determined that a standard infrared LED² and BK7 glass lenses were adequately radiation-hard, and used these components in all systems installed on the detectors. We replaced the CCD camera typically used in previous RASNIK systems with a CMOS-based camera. Such cameras are smaller and are known to be more robust to radiation. Still, we observed that the camera would suffer fatal damage at this dose, but only if it was powered on during the exposure. No visible damage was apparent if the camera was turned off. Since the systems are read out one at a time, we energize each camera (and LED) only when it is being used, and expect no significant radiation damage. This mode of operation corresponds to an approximate 5% duty cycle. After 1.5 years of running, including higher than expected beam losses, no visible effects of radiation damage have been observed on any system.

¹The radiation testing was supervised by David Pellett and Gary Grim at UC Davis. For details of the initial camera testing, see <http://noyce.ucdavis.edu/camtest.html>.

²In general, LEDs which were described by the manufacturer as “rad hard” did not necessarily perform any better than more randomly chosen units. Infrared emitters were chosen to match the peak sensitivity of the camera.

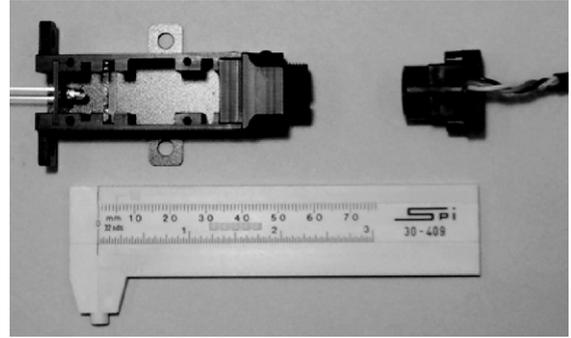


Fig. 3. A photograph of the RASNIK projector (upper lid removed) and camera used in the CDF RASNIK system. The LED and coded mask are visible towards the left (back) of the projector interior. The lens is located within the threaded barrel at the front of the piece. Note that the distance of the mask to the lens may be changed to accommodate different baselines. The lens position may be determined by final focussing in situ.

The accuracy of the two-element system was tested by placing the projector on a moveable stage on an optical bench. Fig. 4 shows the actual vs. reconstructed position of the camera as it was moved horizontally. Similar results were obtained for vertical movement. The figure also shows the residuals, which are unbiased with an RMS of $0.4 \mu\text{m}$. Such accuracy is at the limit of our ability to position the camera and probably does not indicate the limiting RASNIK resolution.

3. CDF implementation and data acquisition

CDF’s silicon system consists of three independent elements: a single layer mounted directly to the beampipe known as Layer 00, an inner tracker (radii: 2.4–10.6 cm) known as the SVX, and an outer tracker (radii: 20.0–28.0 cm) known as the ISL. The entire superstructure is connected at its ends to the inner wall of CDF’s drift chamber (central outer tracker, COT) through piezoelectric positioners, called “inchworms” [7]. Seventeen RASNIKS are strategically placed³ throughout the silicon tracker system so that movements of

³The inchworm system employs a gimbal mount at one of its six support points on which it is not possible to mount a RASNIK. This breaks the placement symmetry described in this paragraph and implies one fewer installed system.

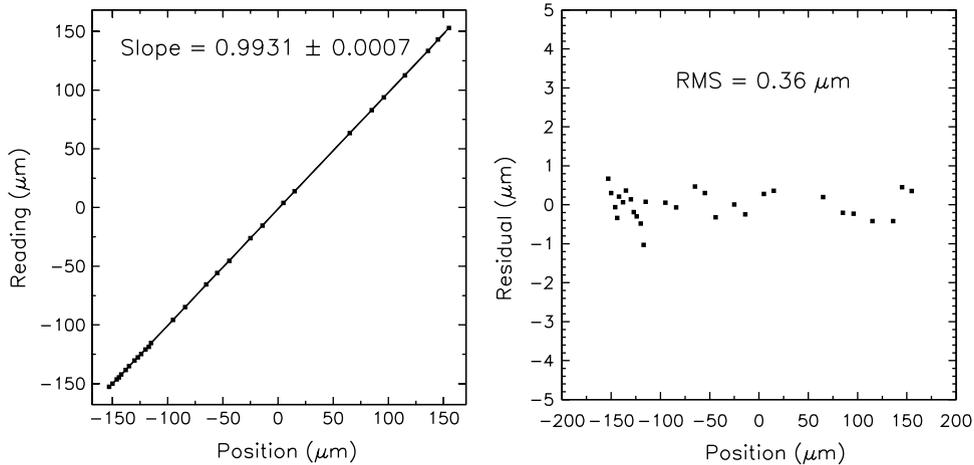


Fig. 4. Testbench results of the two-element RASNIK. Left: Reconstructed vs. actual camera position. Right: Residuals. Note that the $0.4 \mu\text{m}$ residuals probably reflect our ability to position the moveable stage, rather than the limiting resolution of the RASNIK.

particular systems can be combined to determine the global twisting or translational motion of the silicon superstructure. The placement follows a three-fold azimuthal symmetry (following that of the inchworms) with mirror symmetry about the interaction point. A schematic diagram of the placement of the RASNIK systems in CDF is shown in Fig. 5. In addition to the 17 deployed RASNIKS, two systems (one short and one long baseline) are installed as a control in the DAQ rack space. These are mounted on 1/2-in. aluminum plates which are set on vibration damping material, so little relative motion is expected.

The data acquisition is controlled by a 600 MHz rack-mounted PC running Linux, located in CDF's counting room. The data-taking proceeds RASNIK-by-RASNIK through a simple endless loop. For each RASNIK, the PC activates two relays corresponding to low-voltage power (for both the LED and camera) and the output video signal. All signals are carried on ~ 200 ft lengths of shielded twisted pair cable; no degradation of the video signal has been observed. Care was taken to avoid ground loops. When the relay is closed the video signal is connected to a PCI "frame grabber" card which takes the picture. The image is reconstructed in roughly a second, yielding transverse positions (in the plane of the camera's image sensor), a rotation angle of the mask, and several quality-of-fit variables. In addition, a crude

($\sim 100 \mu\text{m}$) measurement of the longitudinal distance between the camera and projector is obtained from the change in magnification of the image. In standard operating mode each RASNIK's position is measured approximately every 120 s. The minimum time necessary to take a data point is limited by the camera: Since the systems are normally unpowered to mitigate damage from radiation, a few seconds must be allowed upon power-up before the camera output signal becomes stable. For special running conditions, such as when the silicon detector position is being changed, a single RASNIK's position can be read out every second. The readout system has proven highly reliable; data taking has proceeded without interruption for almost 2 years. The raw data are archived on disk, and plots of RASNIK data from the current and previous month are available on a web page which is automatically updated every hour. The direct video output from the systems is also viewable in real time on a monitor channel in the CDF control room. A very useful feature, which we plan to implement soon, would be to add a bit to the raw RASNIK data which signifies whether physics data were being taken with the CDF detector. The existing plots on the web page will then display these periods in a different color, so that they will be easily recognizable at a glance.

It is worth noting that the RASNIKS are quite adaptable, and can also be of use as a stand-alone

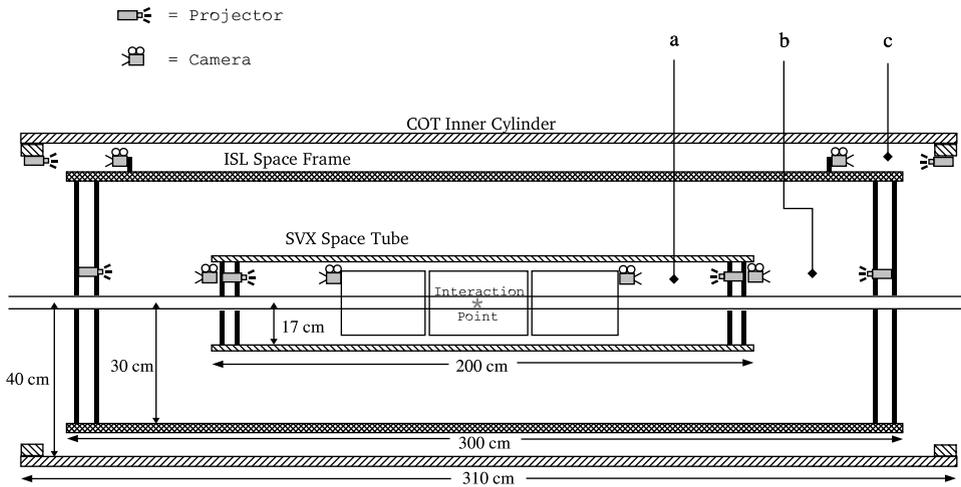


Fig. 5. Diagram (not to scale) showing the placement of representative RASNIK systems inside the silicon tracking system. (a) SVX, (b) SVX \rightarrow ISL, (c) ISL \rightarrow COT (inchworm). The mirror symmetry of the placement is shown here. The systems are repeated every 120° in azimuth (for clarity this is not shown here) yielding a total of 17 (there is one exception to the symmetry, described in the text, which results in 17 instead of 18) systems.

setup, without collecting any data. In October 2000, the silicon detector mounted directly onto the beampipe (Layer 00) was inserted into the inner silicon tracker (SVX). This was a delicate process, with very little clearance margin. Two RASNIKS were orthogonally mounted downstream of the insertion point, with cameras attached to the beampipe and projectors mounted close by on makeshift stands. The RASNIK images were displayed continuously on two adjacent monitors, and provided an instantaneous visual cue to any incidental contact during the insertion.

4. Data

As described in the previous section, two RASNIKS were installed in the DAQ rack space as a control. The data from one day of data taking from one of these systems are shown in Fig. 6. The RMS of the apparent relative motion is $<0.5 \mu\text{m}$; data from the other control system were similar.

Each of the 19 RASNIK systems takes data points in the two transverse (x, y) and longitudinal (z) directions every couple of minutes. In the following figures we show some representative features of the data taken thus far. Fig. 7 shows 1

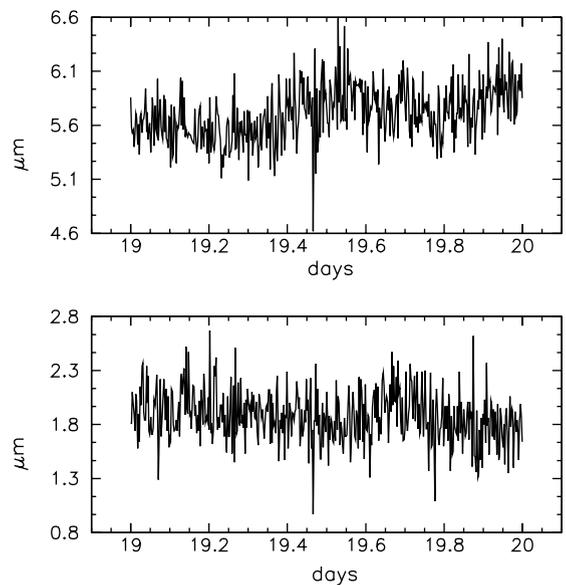


Fig. 6. Data taken from a “control” RASNIK system over a 24 h period. Transverse motions (x and y) are displayed in the upper and lower plots, respectively. This RASNIK was specially mounted and isolated from vibrations, so little movement is expected. The RMS of the movement is $<0.5 \mu\text{m}$.

day of motion recorded in the x and y directions for a quiet period, when CDF was taking data but no changes were made to any voltages or to the solenoid current. The data are shown for one each

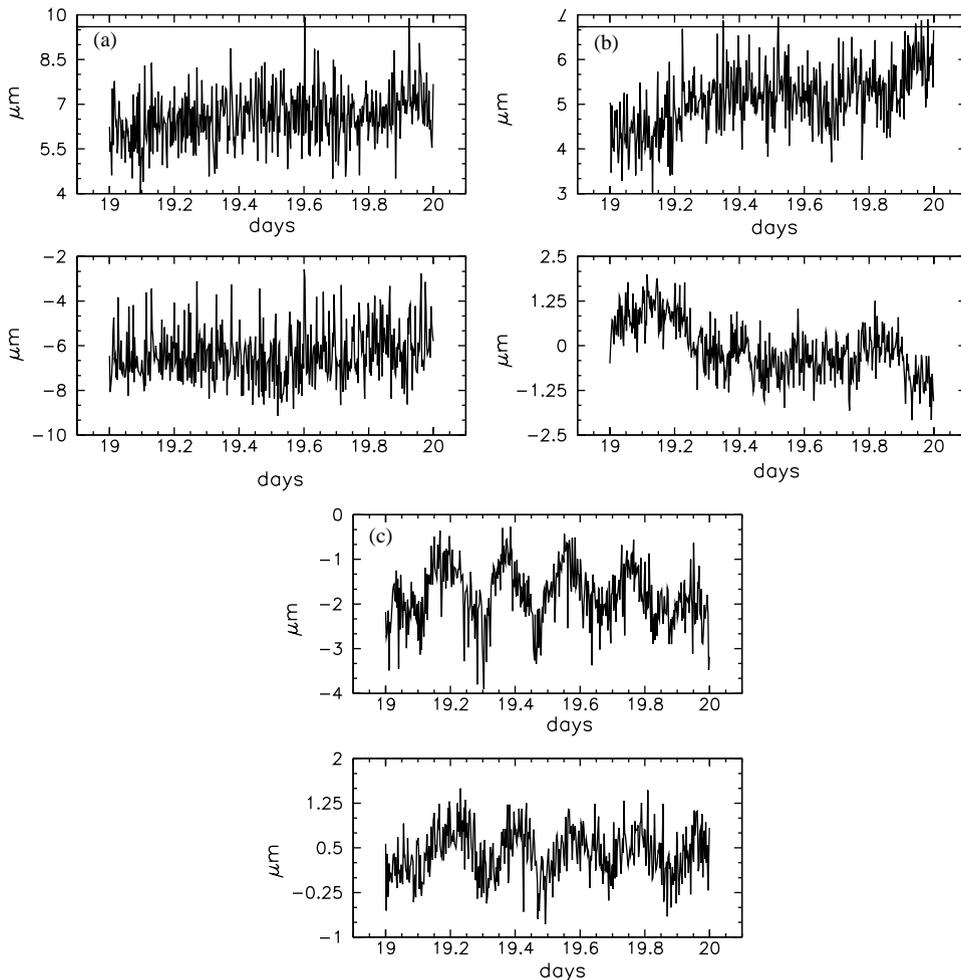


Fig. 7. Transverse motion (x and y) data taken from one of each of the three types of RASNIK systems over a particularly stable 24 h period, i.e., with no changes to the solenoid current or silicon power. (a) SVX, (b) SVX \rightarrow ISL, (c) ISL \rightarrow COT (inchworm). The RMS of the movements during periods with these types of environmental conditions is typically a few micrometers.

of the SVX, SVX \rightarrow ISL and ISL \rightarrow COT (inchworm) systems. The data reflect stability to $< 5.0 \mu\text{m}$. This is a slightly higher variance than the control systems, but is within design tolerances for the CDF tracking detectors.

A more typical day shows large motions, as shown in Fig. 8. The $\sim 30 \mu\text{m}$ feature at 12:50 (at 22.55 days) corresponds exactly to a change in the current in CDF's 1.4 T solenoid. A view of an entire month is shown in Fig. 9. Many of the large motions due to energizing the solenoid, etc. are visible. It is worth noting however that during data-taking periods with silicon included in the

run, the entire system always returns towards its nominal position. The overall behavior thus far in CDF's Run IIa seems consistent with some settling of the detector subsystems: Over the course of a month, some creep in the nominal position has sometimes occurred. This was more prevalent early on, and has tended to diminish with time. It is also interesting to note that motions due to cyclic temperature variations (day/night effects, etc.), which one might expect to see, have so far not been observed. Since the RASNIKS have shown that the silicon trackers are very stable during data taking, the main long-term use of the

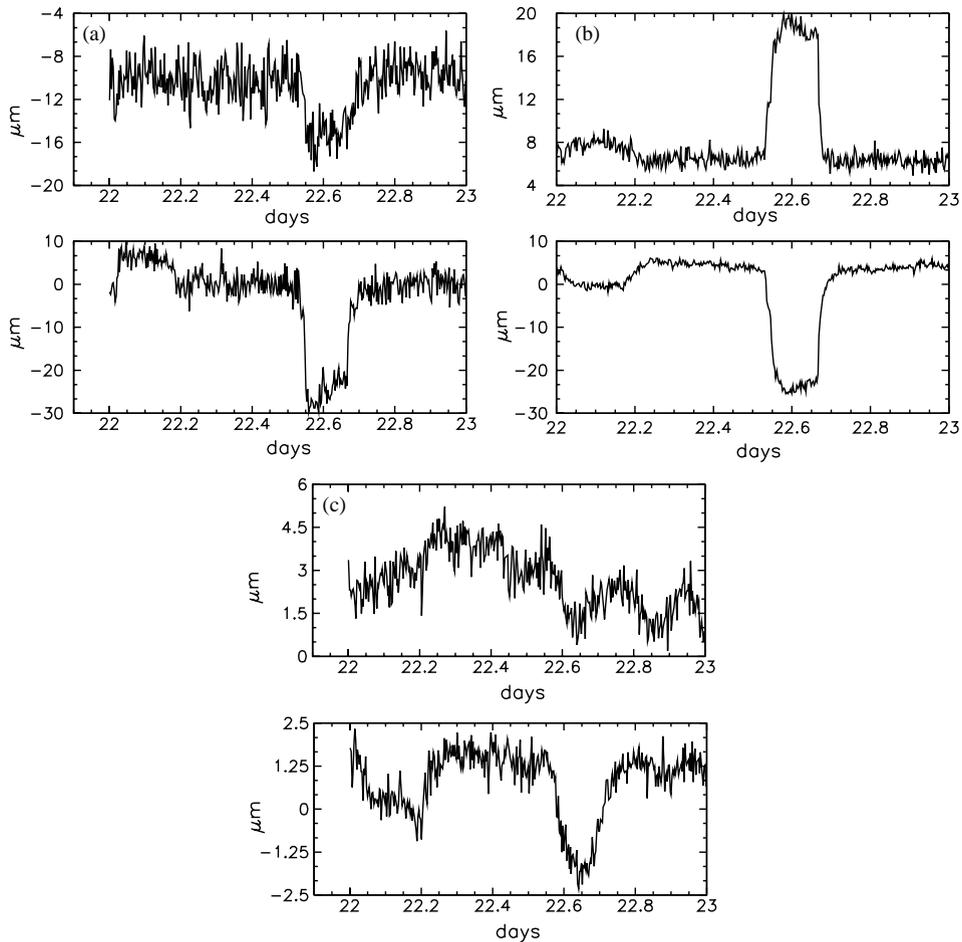


Fig. 8. Transverse motion (x and y) data taken from one of each of the three types of RASNIK systems over a more typical 24 h period. (a) SVX, (b) SVX \rightarrow ISL, (c) ISL \rightarrow COT (inchworm). The large motion at 12:50 (22.55) corresponds to a change in the solenoid current. Note however that the silicon returns to its nominal position during the conditions of data taking.

system will be to flag times when new global alignment periods should be defined.

When considering large motions recorded by some of the systems, it is important to recognize that changes in the angle of the projector piece with respect to the camera can be interpreted as large linear motions as the projected image sweeps across the camera. Because of the placement of the systems at CDF, we can disentangle these effects by performing a global analysis of the motion of all the RASNIKS together. For example, when the cooling to the silicon detectors is switched on or off, a mechanical coupling between the beam pipe

and the inner SVX/ISL structural supports⁴ causes the SVX and ISL systems to record a linear relative translation which is approximately 10 times the actual movement. With the existing system, this effect is discernible by a global analysis of the SVX RASNIKS. The possibility of handling these types of effects on a single-rasnik basis is discussed in the next section.

⁴Note that some mechanical coupling between the beam pipe and the supports was purposely included in the original design, and that the level of coupling observed is consistent with this design.

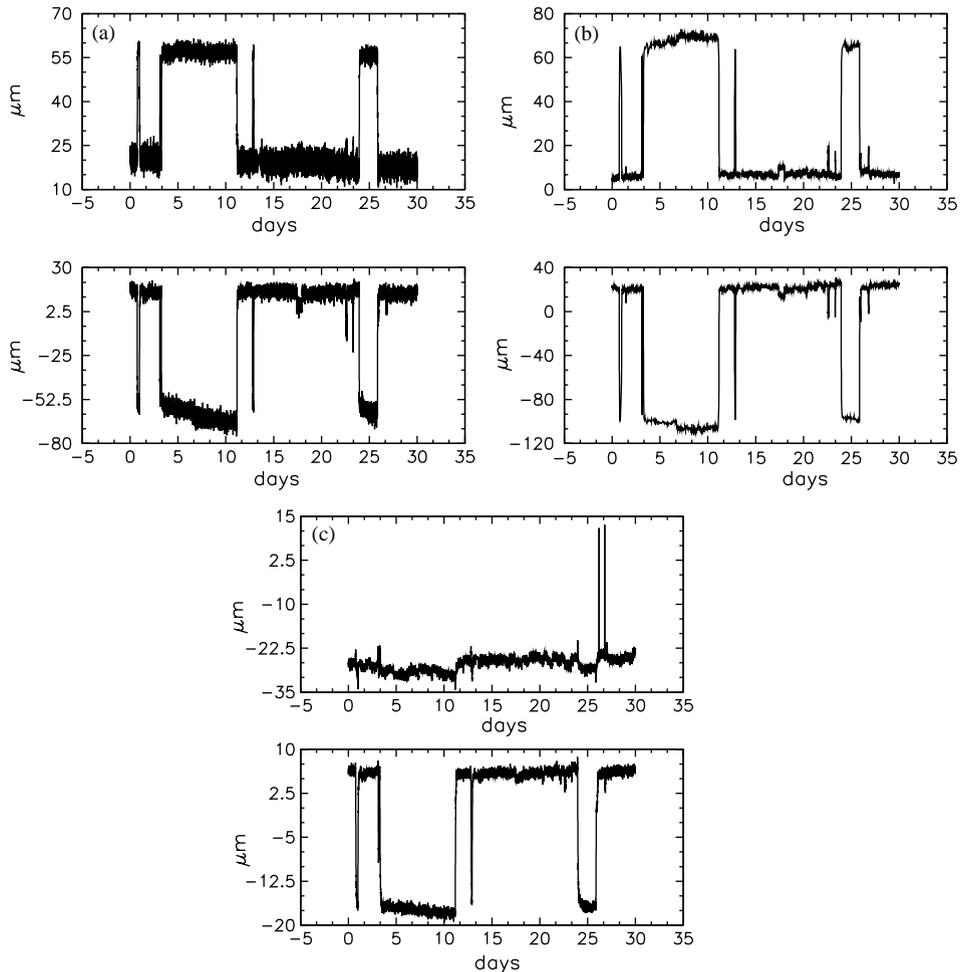


Fig. 9. Transverse motion (x and y) data taken from one of each of the three types of RASNIK systems over a typical 1-month period. (a) SVX, (b) SVX→ISL, (c) ISL→COT (inchworm). Many of the large motions due to energizing the solenoid, etc. are visible.

5. Future improvements

The greatest difficulty in interpreting the RASNIK data from CDF was separating angular tilts of the projector piece (which appear as large translations in the raw data) from true non-rotational displacements. The same systems which were particularly susceptible to this effect also provided, when examined together, a way to determine whether there had in fact been a rotation of the projector piece(s). It would be nice, however, if there were a direct measure of this effect which did not rely on the readout of other

systems. One possibility is that future systems might also deploy a small tilt meter on each RASNIK projector, or on some select units. Small tilt meters are commercially available with angular resolution of order $1 \mu\text{rad}$. For the baselines we use, 15–50 cm, such precision would allow corrections to micrometer precision.

Another improvement would be to employ a more advanced camera. During the last few years, the state-of-the-art in microvideo image sensors has moved to digital output. Instead of an NTSC output signal, a chip in the same size package is now available which has double the resolution and

full digital output. The signal can be transmitted in parallel or clocked out on a single cable to a digital input board, removing the need for a frame grabber. Such a pure digital system would also provide a raw data file with the information from each pixel uniquely identifiable. It may even be possible that one could use this information to gauge tilts of the projector by examining the “squareness” of a projected square from the coded mask.

6. Conclusion

We have developed a modified RASNIK system which is based on two, rather than three elements so that ambiguities in motion have been reduced. We have designed a projector system out of radiation-hard and low-mass components so that systems could be deployed in the inner tracker of the CDF detector. Radiation damage to the installed RASNIKS has been successfully mitigated by operating the systems at a low duty cycle. The RASNIKS have found large motions due to the solenoid and powering of the silicon detectors that would otherwise have been unnoticed since no alignment data are taken during those periods. The RASNIKS have also shown that during data-taking periods the entire silicon tracking system is extraordinarily stable on the minutes to days time scale, giving us confidence that motions are not degrading CDF’s reconstruction or triggering ability. The data-acquisition system has been robust, taking data continuously for almost 2 years with no downtime other than power outages.

The RASNIKS have given CDF a minute-by-minute view of motions of its sensitive inner trackers that would otherwise have been unavailable.

Acknowledgements

We thank Harry van de Graaf for introducing us to the RASNIK system. We thank Brenna Flaughner, Joe Incandela and Rick Snider for advice and support of the RASNIK system within the silicon construction project. We thank Frank Chase for his engineering support during the design and construction of prototypes and production pieces. We are indebted to the technical expertise of Greg Derylo, who guided the final installation onto the CDF silicon detectors. We thank Jim Patrick for helping us deploy the DAQ linux box at CDF. This work was supported in part by the US Department of Energy.

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