Chapter 6: Source location system

The insertion system does not provide enough feedback to give an accurate position of the source needed to verify Borexino's solar neutrino signature. The only way to see that the neutrinos measured in Borexino are from the Sun is to observe the change in the neutrino flux due to the eccentricity of the Earth's orbit. It is possible to find the event position from the timing of the PMTs, but this cannot provide the 2 cm position resolution required. Simulations show that the error in the position of single events is approximately 12 cm [66]. Borexino has been run without liquid inside several times, but once a source was suspended in the detector, dubbed "Air run VIII". This source consisted of ^{210}Po in solution in scintillator in a quartz ampoule. Data was taken with the source in several positions along the vertical axis of the detector. Preliminary analysis of the data showed that in the x and y directions out from the vertical axis the errors were consistent with 12 cm [67]. During the air runs, the bottom 10% of the PMTs had not been installed, which means that the error on the z-axis was quite high. The centroid of the event, however, is quite good. Despite this, having a completely separate location system decouples the calibration program from the PMT timing. We will then have an independent method to locate an internal calibration source.

The system consists of digital cameras that can find an LED, attached to the source, anywhere in the inner vessel. Rays are projected from the cameras towards the LED and the position of the source is then found through triangulation. The camera system is completely remote controllable from a computer and an electronics box, located close to the insertion system in cleanroom-4. Using digital cameras makes the system very versatile and it can be used for several other tasks in addition to the primary task of finding the position of a calibration source. In May 2002 the system was tested to see how accurately an LED could be located in the detector, and to see whether the ±2cm design could be achieved.

6.1 Motivation (Borexino's solar neutrino signature)

The Earth does not follow a circular orbit around the Sun; rather it revolves in an elliptical path with the Sun at one of the ellipse's foci. Therefore, although the Sun produces neutrinos at a constant rate, the flux at the Earth changes throughout the year. The maximum flux occurs when the Earth is at perihelion, closest to the Sun, and the minimum occurs at aphelion, furthest from the Sun. This flux difference from maximum to minimum is about 6.5%. For Borexino, this means that we need to know the fiducial volume accurately enough to see this annual change in the neutrino flux. As explained earlier, the data-taking region, or fiducial volume, is defined in space in order to cut out the gamma background caused by detector materials. This volume has no physical barrier, so it depends on position reconstruction. To calculate the maximum allowable error for Borexino's fiducial volume radius we first take the fiducial volume to have a radius of 3m. Then, if we have a 3:1 signal to noise ratio, we find that the fiducial volume radius needs to be known to approximately ±2cm in order to see the 6.5% annual change in the solar neutrino flux.

The fiducial volume calibration and monitoring can be accomplished with the use of internal radioactive calibration sources, if the source's position can be found accurately enough.

6.2 Conceptual design

If we assume a pinhole camera then one can project a line to a point-light source by starting a ray from the image of the light source on the image plane and pointing that ray through the pinhole. This ray then points directly to the point-light source. If there are two of these cameras and their positions and geometries are known, then the position of this point-light source can be found in three dimensions by finding the point where the rays intersect. The system uses these principles to find the location of an LED attached to internal calibration source.

The system employs seven digital cameras, located on the Borexino SSS, six of which are on mutually orthogonal axes. Digital cameras work like conventional cameras in that they project the image of an object onto a device for capturing the image. In conventional cameras this is light sensitive film, but in digital cameras a charge-coupled device (CCD) is used. A CCD is a device that is effectively a matrix of light sensitive areas called pixels. Each of these pixels can measure the intensity of the light, and are able to measure color by dividing the pixel into red, green, and blue areas. This way the intensity of each color can be captured in order to give us a colored picture.

The digital cameras are equipped with fish-eye lenses so that they can see the entire inner vessel as well as each other. Since the lenses of the camera, including the fish-eye lens, are not in reality pinholes there are added complications to this method. We have overcome this by making corrections to the image, and by constructing a ray from an effective pinhole toward the light source. Once the rays to the point-light source are found then its position can be found through triangulation.

6.2.1 Ray tracing

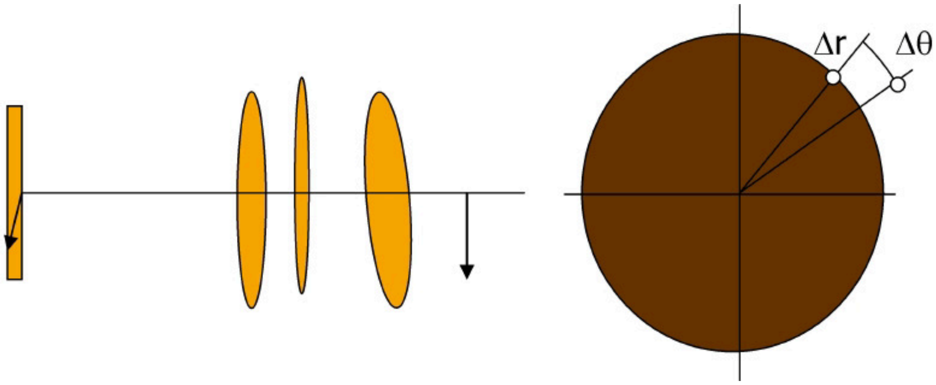

Figure 6.1: Image distortions due to lens geometry. Lens position, shape, and alignment cause distortions in the image on the CCD. The lenses may not be on the optical axis, not perpendicular to the optical axis or the CCD may not be centered or perpendicular to the optical axis.

Within the lens system, many things can cause distortions in addition to the shape of the lenses, for example if a lens is not on the optical axis, or if a lens or the CCD is not perpendicular to the optical axis. The shape of the lenses, misalignments, etc. will show up as a departure of a point on the image from that expected with an ideal pinhole camera in both the radial and theta directions on the image plane (Figure 6.1). These divergences make the ray tracing more of a challenge. To find the path of the ray from a point on the CCD, through the lenses and towards the corresponding point on the object, one needs to know the size, position and shape of every lens in the system, as well as the position and size of the CCD and its pixels. A simpler approach is to assume a pinhole and then correct for the distortions mathematically on the image plane.

The simulated camera geometry has the CCD in front of the “pinhole”, which is the origin of the camera frame. In other words, a ray starts from the origin, passes through a point on the CCD and a corresponding point on the object. Effectively our CCD is just a reflection through the origin (pinhole) of a normal CCD. The coordinate system of the camera is a left-handed system with the *z*-axis pointing through the CCD, the *x*-axis to the right on the image, and the *y*-axis is vertical. The left-handedness of the camera’s coordinate system makes the transformation from the camera frame to the detector frame easier in the software. In our simulation of the camera, the distance of the CCD along the z-axis is fixed, and the CCD size and the scales of the pixels are left as free parameters. We have left the pixel scales free in both the *x* and *y* dimensions on the CCD because the pixels are not necessarily square, they may be rectangular. In addition, because the center of the real CCD may not coincide with the optical axis, there are offset parameters in the *x* and *y* directions as well. Since the image the digital camera produces is a direct map of the pixels on the real CCD, we can use it to find all these parameters. The image gives us the number of pixels in each coordinate, from which we can find the scale of the pixels. It also gives us the offsets parameters once the camera position is known. Once we have this information, we can begin to correct the image due to the distortions of the lenses.

As was mentioned earlier, the divergences in the image, due to the lenses, can occur in both the r and θ directions on the image. In our analysis, we did not find an angular dependence; therefore, corrections were only made to the radial component. This correction was made by fitting a 9th order odd polynomial, Equation 6.1, in the radial direction on the image plane or CCD. [68]

$$r_{corr} = \sum_{i=1,3,5,7,9} c_i r^i \qquad c_i = \mathit{lens\ correction\ factor}$$

Equation 6.1: Polynomial to correct the distortions in the images due to the lenses.

At this point we know the parameters that define the camera, but we also need to know the position of the camera’s origin and the orientation of the camera’s coordinates in the detector’s frame. The position of the camera origin is just a mater of finding the effective pinhole of the digital camera, and placing it in its known location. Then the camera frame can be rotated about each coordinate until the simulated camera’s coordinates match the real camera's *x*, *y*, and *z*-axes. Borrowing terms from aviation, the rotations about the axes are called the roll, pitch and yaw of the camera. Figure 6.2 illustrates our simulated camera and shows all the parameters that we have discussed.

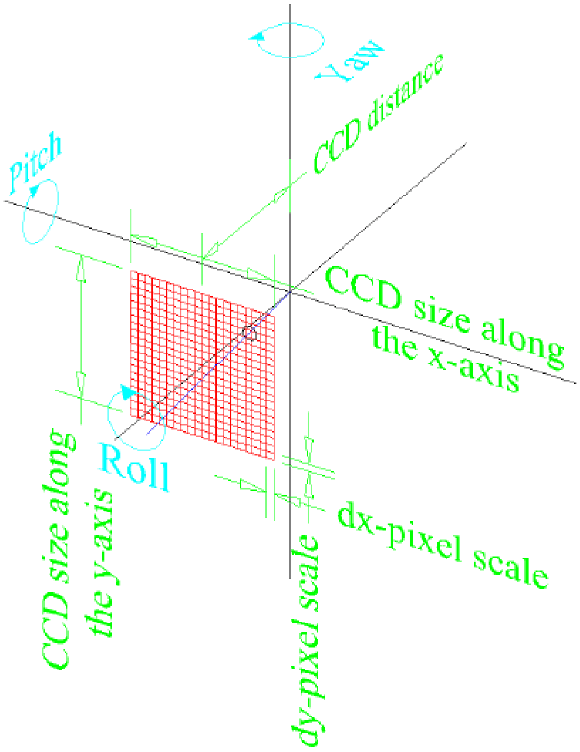

Figure 6.2: Illustration of simulated camera. This shows all the parameters that go into defining the camera, including the rotations that orientate it to point in the right direction. Roll is a rotation about the z-axis. Pitch is a rotation about the x-axis. The origin is placed at the same point as the effective pinhole of the real camera. The blue line is an example of a ray that points towards an object from the pinhole and the circle on the CCD.

By using the known positions of the PMTs in Borexino we can find the lens correction factors for each camera in the location system: offsets, pixel scales, roll, pitch and yaw. The pixel coordinates of a point in an image can be corrected for and the corresponding point can be found in the camera frame. By using this point and the effective pinhole we have the two points needed to define a ray, which will always point towards the object that the image point corresponds to. When one has two or more rays that point towards the same object, then the coordinates of that point can be found in three dimensions. For example, the object may be an LED attached to the calibration source.

6.2.2 Triangulation

Due to the limited resolution, the rays from the cameras do not in general cross each other at the same point. To overcome this, a minimization routine is used to find the position of the object the cameras are locating. First a point is defined in the detector and then the coordinates of points on the rays which correspond to the shortest distances to that initial point are found. A least squares method is employed to find the most likely position of the point being located. *X* in Equation 6.2 represents the sum of the squares of the distances between the shortest distance points and the point in space, x_{LED}. Minimizing *X* finds the position of the LED.

$$X = \sum_{i=1}^{7} (x_i - x_{LED})^2$$

Equation 6.2: Sum of squares of distances from the presumed LED position and the point on the ray which is closest to the LED position.

In May 2002 a test of the system was run. This gave us the opportunity to find the resolution of our system and the error in a position measurement.

6.3 Actual design

The system that was built uses Kodak DC290 digital cameras with a Nikon FC-E8 fish-eye lens. Connection from the camera to the computer is via Universal Serial Bus (USB), which has a faster data rate than the RS-232 serial connection which is also available. However, the USB connection requires a repeater due to its limited cable length capabilities. Being a consumer-grade zoom camera and not a scientific grade camera the lenses move in and out of the camera body when it is turned on and off, and whenever a picture is taken. The reproducibility of the lens position with each movement needs to be measured, and to do this with every run each camera assembly is also provided with LEDs similar to the source LED. To illuminate the detector for general pictures of the inner detector each camera assembly is equipped with halogen lights. The entire camera assembly is installed into a stainless steel housing on the SSS. An electronic control box serves as the nerve center for the camera system and it is controlled with a Windows based PC in cleanroom-4, where the source insertion system is also located.

6.3.1 The camera housing

The camera housing in Figure 6.3 is a stainless steel can affixed to the SSS. The camera assembly, described in the next section, installs from the rear, and an eleven-inch flange seals the camera housing from the water tank with double viton o-rings. The seal between the camera housing and the SSS is a stainless steel Helicoflex seal, because it emanates less radon than elastomer seals. The same type of viton material used for the PMT o-rings is used for the o-rings used to seal the glass dome.

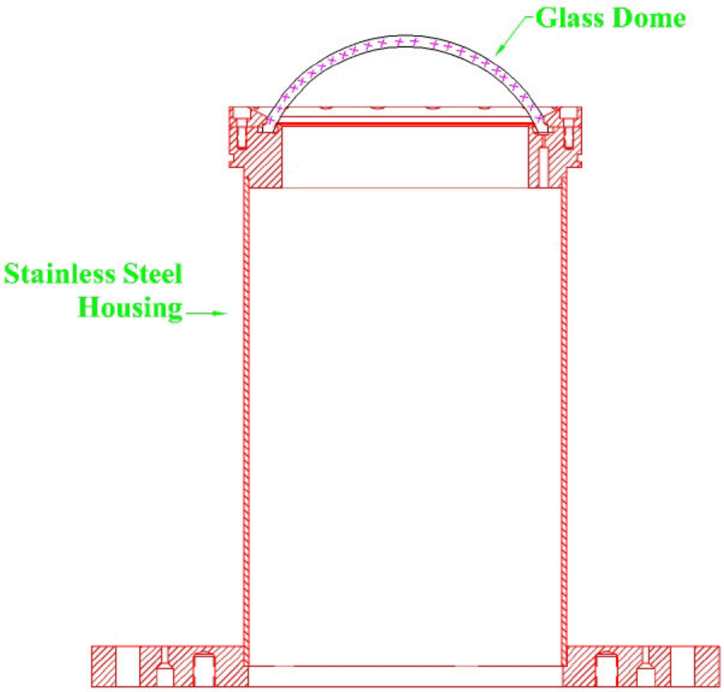

Figure 6.3: Drawing of camera housing, which is mounted on the SSS. The camera assembly is installed from the rear, and sealed with a flange. This method allowed us to have access to the cameras until the detector starts to fill with liquid.

The glass dome is a very important part of the camera housing. The optics of the detector forced us to use a spherical dome to be able to see the entire detector. A flat window would have limited our view to an opening angle of about 80° due to total internal reflection; this does not take into consideration that the camera does not sit directly against the window, which will further decrease the possible opening angle with a flat window. The Subal Company in Austria, which makes underwater camera housings, was able to provide us with spherical glass domes. The dome has a minimal effect on the optics in air, but when the detector is filled with a liquid, there may be a difference. The magnification can be eliminated if one puts the effective pinhole lens of the camera at the center of the spherical dome. Images will now look the same whether the pictures are taken with the detector filled with gas or liquid, or liquids with different indices of refraction. We therefore found the effective pinhole of the camera/fish-eye lens combination, Figure 6.4 (refer to section 6.3.2), and mounted the lens/camera assembly so that this effective pinhole was at the center of the glass dome.

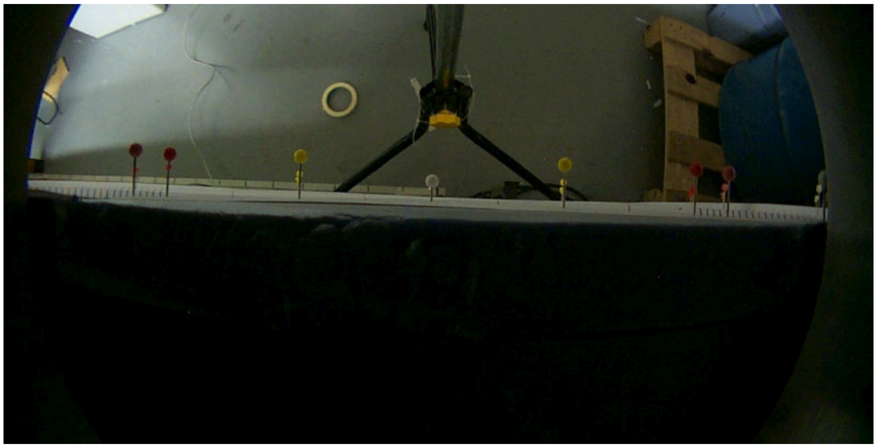

Figure 6.4: Effective pinhole determination. This was found by taking a picture of pins which are aligned to point towards a single point. When they are lined up in the picture then the effective pinhole can be found in relation to the camera.

When the detector is filled with a liquid, the glass dome will act as a lens. Although we do not have to worry about magnification with the effective pinhole at the center of the dome, we do have to worry about the focusing ability of the camera. The gas/glass interface of the dome is the refracting surface where the lensing will occur. The camera will have to focus onto the image the dome produces of the object. To find out if this is possible we need to know where the image will be. Since the radius of the dome is 93 mm we can calculate the position of the virtual image the refracting surface produces. For a spherical refracting surface of radius R, one can trivially find

$$\frac{n'}{l'}+\frac{n}{l}=\frac{n'-n}{R}$$

which gives the position *l'* of the virtual image of an object at *l*.

If we use the distances closest and farthest from the dome, which are about 2.50 and 10.75 meters, respectfully, and the indices of refraction for pseudocumene and air, approximately 1.5 and 1.0, respectfully, then we can find the virtual images the dome will produce. These distances are 16.7 cm in front of the dome for the closest object and 18.1 cm for the furthest object. One can see that the depth of field for a lens like this is very large, the virtual images we need to focus on change very little when object distances differ greatly. We tested the camera and fish-eye lens combination to see if it was possible to focus so close, since the closest the camera is able to focus is 0.5 meters, refer to Table 6.1. The results showed that it is possible for the camera/fish-eye lens combination to focus on the virtual image that the dome will produce, which is not surprising, since the fish-eye lens also produces a similar effect to the depth of field. With the fisheye lens, we are able to focus on the opposite side of the detector, which is about 13 m away, and it will work when filled with liquid.

6.3.2 The camera assembly

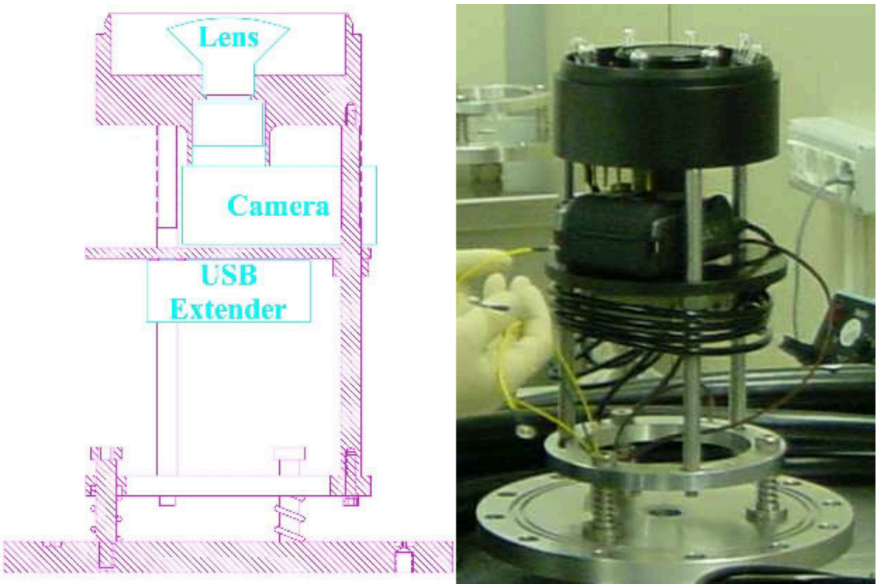

Figure 6.5: Camera assembly. The camera assembly contains the camera, additional fish-eye lens, lights, LEDs, USB extender, and is all installed into a housing on the SSS on the displayed mounting structure.

As mentioned above, the camera used in the system is the Kodak DC290 zoom digital camera. Table 6.1 gives the camera specifications from Kodak [69]. This camera was chosen over other models at the time, due to its high resolution and its computer friendliness. Kodak not only made available a software package so that one could write a custom software package to control the camera, but the Digita™ script language, which runs the camera locally, opens many possibilities to control the camera.

DC290		
Pixel Resolution	**CCD**	1901 x 1212 = 2.3 millions of pixels (total number of pixels)
	Ultra	2240 x 1500 = 3,360,000
	High	1792 x 1200 = 2,150,400
	Medium	1440 x 960 = 1,382,400
	Standard	720 x 480 = 345,600
Color		24-bit, millions of colors
Picture File Format		Exif version 2.1 (JPEG base) or TIFF
Picture Storage		External memory only: ATA compatible CompactFlash card
Viewfinder		Real image
ASA/ISO Sensitivity		100
Flash Range	**Wide**	1.6 ft to 13.1 ft (0.5 to 4.0 m)
	TelePhoto	1.6 ft to 8.2 ft (0.5 to 2.5 m)
Lens	**Type**	Optical quality glass
	Maximum	**Wide:** F/3
	Zoom	6X:
	Focal Length	38.4 to 115.2 mm (equivalent to 35mm camera)
	Auto Focus	**Wide/TelePhoto:** 1.0 ft (0.3 m) to infinity
	Manual Focus	**Wide/TelePhoto:** 1.6 ft (0.5 m) to infinity
Power	**Batteries**	AA size 1.5 alkaline, or AA size 1.2 volt Ni-MH rechargeable
	DC Input	AC Adapter for Kodak DC200 Series Digital Cameras
Tripod Socket		.25 in (.006 m) threaded
Video out		NTSC or PAL
Dimensions	**Width**	4.6 in. (118 mm)
	Length	2.5 in. (63 mm)
	Height	4.2 in. (106 mm)
Weight		1.2 lbs (525 g) without batteries
Operating Temperature		32 to 104° F (0 to 40° C)

Table 6.1: Camera specification for the Kodak DC290 Digital Zoom Camera.

Our application has some requirements that the DC290 did not meet and therefore we needed to modify the camera. The ideal situation would have been to use completely remote controllable scientific grade cameras, but the camera that had a resolution high enough for our purpose was many thousands of dollars and, therefore, was cost-prohibitive. Unfortunately, the DC290 does not have a remote on/off switch, so we had to hard-wire the power switch. Another issue was the shutter release timing. We need the cameras to take a picture simultaneously to minimize the time the LEDs must be on. The Kodak software package did not allow simultaneous shutter releases. The software package developed to control the camera system will be described later in this chapter. Therefore we also had to hard-wire the shutter. An additional issue is that the DC290 lenses are not removable, and therefore could not be replaced with a lens that had a large enough opening angle. We required that, at minimum, each camera needed to be able to see the entire inner vessel.

In order to see the entire inner vessel, and to insure that the cameras can see each other, it was necessary to equip each camera with a fish-eye lens. Kodak does not offer a fish-eye lens for the DC290 as an accessory, so we had to use a Nikon FC-E8. Kodak's own lens adapter and lenses use a 37 mm thread, while the Nikon lens uses a 28 mm thread. This required a custom mount to hold the lens and camera. The lens screws into this mount, Figure 6.5, and the camera attaches to the other end in the same way as it fits the Kodak DC290 lens adapter. This mount is also where the halogen lights and LEDs are located. Figure 6.6 shows a picture of the inside of the mount with the lights, LEDs and lens installed. An important feature of the lens/camera mount is that it keeps light that may be in the camera housing (described in the next section) from entering the detector. The camera has LEDs and an LCD screen, which were not disabled for fear of damaging the camera. However, they were covered with black tape. To make electrical connections on both sides of the mount, brass screws are threaded completely through it. This allows us to provide an electrical connection through the mount without creating a light leak. The mount indexes off the flange that the dome seals to, which locates the effective pinhole of the camera system at the center of the dome.

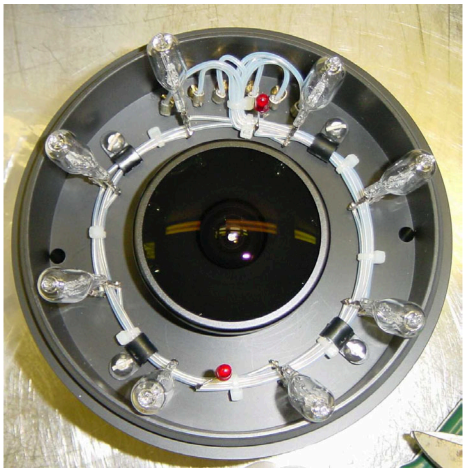

Figure 6.6: Lens/camera mount. The lens/camera mount also contains the lights and LEDs. The holes are for a nitrogen purge.

The camera can connect to a computer through either RS232 or USB. USB has the faster data rate, but has a limited cable length. To have a USB device further than 2 meters away from a computer a repeater must be used. The USB extender we use is a Blackbox® Remote Port USB model IC240A. This repeater has remote and local units, and transports the signal over a CAT5 UTP cable up to 100 meters. The remote unit is located inside the camera housing and the local unit resides in cleanroom-4. In the Borexino counting test facility (CTF), three cameras were installed without USB repeaters and used RS232 instead. With picture file sizes over 7 megabytes (Mb), the RS232 proved to be far too slow. These pictures took several minutes to reach the computer. Without the USB connection, the seven pictures from Borexino would take up to 105 minutes to upload. This is too much time if the system is to be used while moving the source into position. The remote repeater unit is mounted in the camera assembly on the so-called "USB extender mount", which also pushes the camera against the lens/camera mount to make sure that it cannot fall off, Figure 6.5.

The lights used to take general pictures are 50-watt 120-volt quartz halogen bulbs available at a local hardware store. To accommodate the 220-volt line voltage in Europe, two of the bulbs are wired in series. Two sets of the two bulbs in series are then wired in parallel to form a cluster of four bulbs. This cluster of four bulbs provides 200-watts of lighting in each camera housing. When a general picture of the interior of the detector is taken, six camera housings are illuminated and the seventh takes a picture, which means the detector is illuminated with 1200 watts of light. Figure 6.7 shows an example of the type of pictures that can be taken with these lights. One can see the lights around the periphery, which cannot be used because the light will reflect off the dome and swamp the CCD. Wiring the lights in parallel protects the cluster from completely dying if one bulb burns out. A test conducted at Virginia Tech on ten bulbs wired in parallel, to see how many on/off cycles it takes to burn one of the bulbs out, showed that none burned out after over 10,000 cycles. If Borexino were expected to run for ten years then we would need to take three pictures every day to match what was run at Virginia Tech; therefore, the likelihood of a bulb burning out is very low. However, to be on the safe side each camera assembly is fitted with two light clusters, each of which is controllable from the outside of the detector.

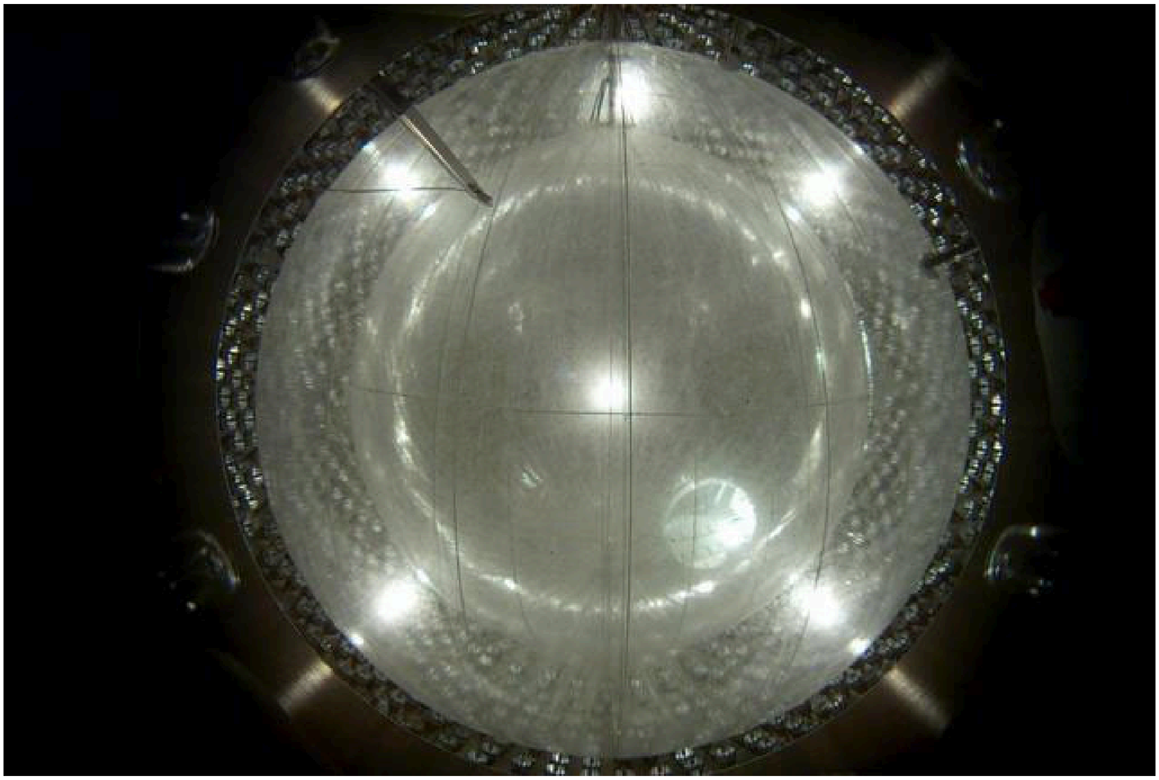

Figure 6.7: Borexino picture with vessels. Interior picture of Borexino, with vessels installed, using a source location system camera. Only the lights in the other camera housings are used, which are the six bright spots.

All the electronics, LEDs and lights in each camera assembly require many cables and wires. The camera needs two wires for the on/off switch, two wires for the shutter, and two power cables. A CAT5 cable is needed for the USB repeater. Three wires are needed for both the lights and LEDs: one a “ground” and one for each light cluster or LED. A black polyethylene tube acts as a conduit for all the wires as well as a separate smaller poly tube. This poly tube flushes the camera housing with nitrogen to remove air and humidity, which might condense onto the glass dome. There are also a few extra wires that were installed in the conduit as a precautionary measure, but were not needed in the end. Table 6.2 lists the wire colors and what they are connected to.

Wire color and size (American Wire Gauge)	Function		Wire color and size (American Wire Gauge)	Function
Red – 22 AWG	Camera on/off switch		Blue – 18 AWG	LED ground
Black – 22 AWG	Camera on/off switch		Yellow – 18 AWG	LED cluster #1 – 5 volts DC
Green – 22 AWG	Camera shutter		Yellow – 18 AWG	LED cluster #2 – 5 volts DC
White – 22 AWG	Camera shutter		Brown – 18 AWG	Extra
Green – 14 AWG	Light ground		Orange – 18 AWG	Extra
White – 14 AWG	Light cluster #1 – 220 volts AC		Gray – 18 AWG	Extra
White – 14 AWG	Light cluster #2 – 220 volts AC		Purple – 18 AWG	Extra
Red – 14 AWG	Camera power – 7.5 volts DC		Light blue – 14 AWG	Extra
Black – 14 AWG	Camera power ground		Purple – 14 AWG	Extra
Blue – CAT5	Signal cable			

Table 6.2: Camera cabling. This table lists the wires in each conduit leading to a camera assembly and what they control. The numbers for the light and LED clusters have no meaning, since we distinguish one cluster from another.

Shoulder bolts and springs mount the camera assembly to the eleven-inch flange, which mounts the assembly in the camera housing. The spring loaded mount provides pressure so that the lens/camera mount will sit flush and tightly against the dome flange on the camera housing. The entire camera assembly and flange structure, Figure 6.5, also made the installation simpler by just having to install one solid piece rather than several independent pieces. The separate items were collected together to form the camera assembly in a controlled environment (rather than trying to install everything on the side of the SSS). Figure 6.8 shows the camera assembly installed in the camera housing, which is mounted on the SSS.

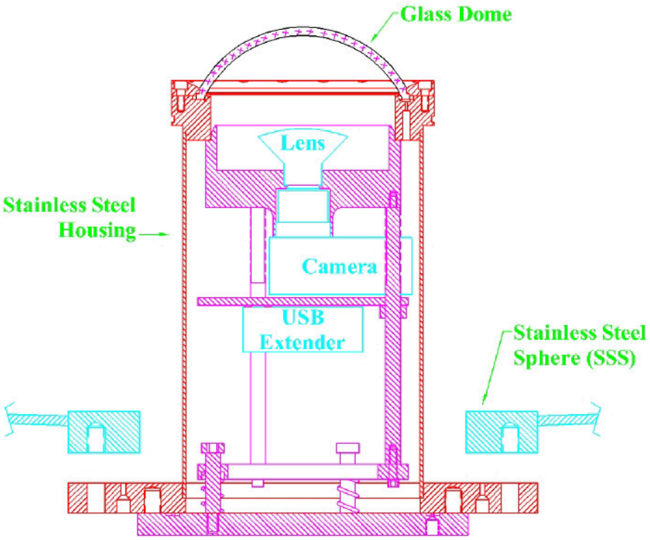

Figure 6.8: Camera assembly mounted inside the camera housing. Notice that the camera/lens mount locates the camera relative to the dome. The completed housing is mounted on the SSS through a DN250[†] flange.

6.3.3 Radioactivity of materials

A common theme throughout this dissertation is concern over contaminating Borexino with radioactive isotopes, or anything that might make the overall background of the detector go up. This is no different for the camera system. The two possible concerns are if the camera housing can release radioactive contaminates into the outer buffer liquid, and "what is the rate of gammas from the system that can reach the inner vessel, both of which will raise the total singles rate?"

The camera housing is made from known materials and is cleaned thoroughly before installation. The radon emanation of stainless steel and glass are insignificant due to the relative surface area of the housing compared to the surface area of the stainless steel and glass already on the SSS. However, the added mass of o-ring material may be of concern. The same company that made the o-rings for the PMTs makes the o-rings for the glass dome with identical material. With nearly 2500 o-rings for the holes in the SSS, the additional 1.5% of mass from our seven o-rings is minimal. The primary concern then becomes the radioactive isotope impurities in all the material, which emit gammas. Table 6.3 lists the major contributors and the values for all the PMTs. One can see that the added activity from ^{238}U and ^{232}Th is negligible compared to the PMTs; however, ^{40}K is

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[†] DN is a German flange standard used in Europe, the DN250 has an inner diameter of 250mm.

85% higher than the PMTs. The ^{40}K in the PMTs accounts for only 5% of the total external background, therefore the cameras system will only add 9% to the overall background, which has been determined to be acceptable [68].

	^{238}U (Bq)	^{232}Th (Bq)	^{40}K (Bq)
Camera	1.3±0.2	2.0±0.2	6.0±1.5
Lenses	≈ 0	≈ 0	140±25
Glass dome	3.0±0.6	0.5±0.1	970±150
USB extender	0.231±0.032	0.274±0.045	0.306±0.015
Sum	4.53	2.77	1116
Total (Sum x 7)	**31.7**	**19.4**	**7800**
PMTs	3000	450,000	4200

Table 6.3: Radioactive impurities in camera housing and camera assembly compared to PMT contribution.

6.4 Control system and software

Having described the method and mechanics of the location system, we will now discuss how it is all controlled with both electronics and software. The conduit that leads all the wires listed in Table 6.2 to the camera housing come out in cleanroom-4. The CAT5 cable from the USB extender meets its counter part, the local unit, and from there is connected to USB ports on the computer. There are also the wires that power the lights, the LEDs, cameras and the wires for the on/off and shutter switches on the camera. All these run to a control box connected to the computer's serial port. The idea is that we want to be able to turn on and off any of the lights, any of the LEDs, and any of the cameras, and only have pictures taken with certain cameras. In other words, we want total control of the system. By having the control box as an interface between the camera assemblies and the computer we have accomplished this. Software developed at Virginia Tech runs the control box, and uploads and downloads from the camera. It will also find the source LED in the detector, and is used to calibrate the location system.

6.4.1 Control box

Figure 6.9: The camera control box. It is the interface between the computer and the camera system.

Each device is connected to a relay that either closes a circuit, camera on/off and shutter, or connects power to the device, lights, camera power and LEDs. A flip-flop on each relay maintains the relay's state, and changes it when instructed to.

The control box contains everything needed for the camera assembly, except the local unit for the USB extender. Camera power supply, LED power supply, USB extender power supply, and detector safety systems are all located within the control box, which is pictured in Figure 6.9. The lights operate on the 220-volt European line voltage, so they are attached to isolated power relays in the box. The timing for most of these devices is not critical. It does not matter when the camera power supply is on, just that it is on when it is needed. Timing is more of concern for the camera shutters and LEDs. All the LEDs are flashed while the PMTs are on so their time and duration must be exact to minimize light exposure of the PMTs to minimize their dark rate. By the nature of the system, no more than one address can change states at the same time. Thus an electronic enable-and-execute method is employed. Each device in a group has a relay to enable it, and the enabled devices are then executed by a single relay connected to the group as a whole. For example the camera shutters need to be simultaneous, but we may not want to use all the cameras, therefore we enable the cameras we want to take pictures from and then release the selected shutters with a single relay. This enable-and-execute method is used for the lights and LEDs as well. This way they can be flashed at the same time and for the same duration.

The control box also has a few safety features. Because the lights are so powerful, and get very hot with time, they cannot stay on for too long since the lens/camera mount is made from plastic and can melt. A timing protection circuit will turn off the lights if they are on for more than 10 seconds, which is more than enough time to take a picture. To guarantee that the lights cannot turn on when the PMT high voltage is on, a lockout switch controls the power to the lights. The lights also have their own power cord from the control box, so if one wanted further assurance that the lights cannot come on they can be unplugged without affecting the rest of the camera system. This also allows us to have everything, except the lights, on an uninterruptible power source. If there is a power failure we can still shut down the cameras and the computer properly since the lights are not needed for this.

The Control Box was originally designed to be run from the parallel port of the computer; however we later found it easier to use the serial port. This required a circuit to change the serial port signal into the parallel port language that the box needs. This circuit unfortunately had the draw back that when it is powered up it enables and latched all the relays. This is unacceptable since it will flash: LEDs, lights, turn cameras on/off, etc. By installing an “output enable” switch, we were able to fix this problem. When the box is first powered up a push button switch must be pushed before it will talk to the camera assembly.

The LEDs in the camera housings and the source LED are all flashed while the PMT high voltage is on. This was tested at Virginia Tech and in Borexino. The test showed that although the PMTs are saturated with light, they recover very quickly. The dark rate returned to normal in less than ten seconds. However, this requires that the data acquisition (DAQ) trigger is inhibited while the PMTs are saturated. The box has been equipped with a NIM logic based inhibit output that is connected to the Borexino DAQ. One might think that turning off the high voltage would be an easier method to ensure PMT safety, but history shows that as PMTs fail, which is inevitable, there is a reluctance to turn the high voltage on and off too much (Also, the gain may change if the high voltage is cycled) .

To see the state of every relay in the control box, LED indicators are located and labeled on the front panel. To measure if a camera is on, the camera control box has an LED marker that shows if the camera is drawing current or not. The camera can be on and not connected if it is asking for an input. This can happen if the power to the camera is cut without shutting the camera down then it will forget the time and date. When the camera is turned on again, it will ask for the time and date, but this happens on the camera, which we do not have access to. If the camera is turned off and then on again it will reset the clock to 12:00 on 01/01/2000, and will then connect.

6.4.2 Control software

A software-package was developed at Virginia Tech to run the control box, control the cameras, and to find the source location. This package is divided into several parts, but can be organized into two major groups: the control software and the analysis software. The control software takes pictures, changes the camera parameters, and can upload the pictures. The analysis software finds the LED in each picture and then the position of the source LED in Borexino. It is also used for calibration of the system. The analysis software will also help during the insertion of sources, since it can provide valuable information about the state of the hinge and its location. The analysis software will be described in the section 6.5 “Calibration, image analysis, and source locating”.

The software is set up with a front-end written in Perl/Tk, which provides a graphical user interface (GUI). From the front-end the different control and analysis packages are controlled. Most of the control software is also written in Perl/Tk, but anything that involves a mathematical or iterative process is written in Fortran 77. The main window, Figure 6.10, accesses the five main processes that are controlled with the software. In the next two sections I will discuss each of these five packages.

Figure 6.10: Main window for the software. From here all the software applications are accessible.