APOLLO Image Orientation

December 3, 2005

Associated with APOLLO are a number of image planes, all with their own orientations relative to the sky. This document develpos the image orientation at each plane.

1 Field Rotation

We start with the hard part: the turning mirrors called M6 and M7 turn the receiver beam through 180°, but also raise the height from 61 mm off the optical bench to 4.5 inches off the optical bench. To do this, the two mirrors are rotated about the incoming beam direction by $\theta = 21.33°$. This affects a field rotation, and this is the focus of this section.

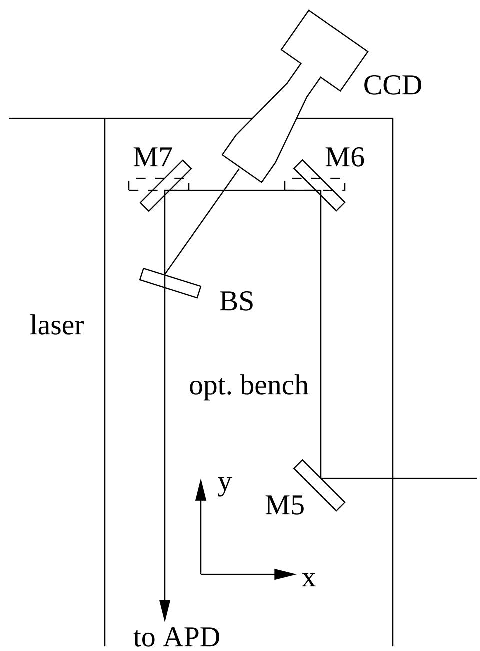

Figure 1: Establishment of coordinate system and labeling of optics.

First, let's set up a coordinate system on the optical bench: the x-direction points toward the quaternary mirror (or ladder on the primary mirror cell); the y-direction points up toward the sky (optical axis of telescope); the z-direction is right-handed, perpendicular to the bench, and pointing outward from the bench (see Figure 1). To find the normal vectors associated with mirrors M6 and M7, we start them out with $\hat{\mathbf{n}}_6 = \hat{\mathbf{n}}_7 = -\hat{\mathbf{j}}$, then rotate about the z and then the y axes: $\hat{\mathbf{n}}_6 = -\mathcal{R}_y(\theta)\mathcal{R}_z(-45°)\hat{\mathbf{j}}$, which comes out to $\hat{\mathbf{n}}_6 = \frac{1}{\sqrt{2}}\langle -\cos\theta, -1, \sin\theta\rangle$; and $\hat{\mathbf{n}}_7 = -\mathcal{R}_y(\theta)\mathcal{R}_z(45°)\hat{\mathbf{j}}$, which comes out to $\hat{\mathbf{n}}_7 = \frac{1}{\sqrt{2}}\langle \cos\theta, -1, -\sin\theta\rangle$.

If a ray comes in with a ray direction $\hat{\kappa}$, and encounters a specular surface with normal $\hat{\mathbf{n}}$, the resultant reflected direction is $\hat{\kappa}' = \hat{\kappa} - 2(\hat{\mathbf{n}} \cdot \hat{\kappa})\hat{\mathbf{n}}$. We can cascade two such transformations pertaining to M6 and M7. Recognizing that $\hat{\mathbf{n}}_6 \cdot \hat{\mathbf{n}}_7 = 0$, this concatenates to $\hat{\kappa}'' = \hat{\kappa} - 2(\hat{\mathbf{n}}_6 \cdot \hat{\kappa})\hat{\mathbf{n}}_6 - 2(\hat{\mathbf{n}}_7 \cdot \hat{\kappa})\hat{\mathbf{n}}_7$. Taking the vectors developed above for

$\hat{\mathbf{n}}_6$ and$\hat{\mathbf{n}}_7$, we find that if we set $\hat{\kappa}_0 = \hat{\mathbf{j}}$, then $\hat{\kappa}_0''$ computes to $-\hat{\mathbf{j}}$, having turned 180°, as expected. The zero subscript here denotes the nominal optical axis. The more interesting question is to ask what happens if $\hat{\kappa} = \hat{\mathbf{j}} + \delta$, where δ is an infinitesemal vector of magnitude ϵ that we will take in turn to be in the $\hat{\mathbf{i}}$ and $\hat{\mathbf{k}}$ directions.

For $\delta = \epsilon\hat{\mathbf{i}}$, we find that $\hat{\kappa}'' = \left\langle \epsilon - 2\epsilon\cos^2\theta, -1, 2\epsilon\sin\theta\cos\theta \right\rangle = \hat{\kappa}_0'' + \epsilon\left\langle -\cos 2\theta, 0, \sin 2\theta \right\rangle$. Likewise, for $\delta = \epsilon\hat{\mathbf{k}}$, $\hat{\kappa}'' = \left\langle 2\epsilon\sin\theta\cos\theta, -1, \epsilon - 2\epsilon\sin^2\theta \right\rangle = \hat{\kappa}_0'' + \epsilon\left\langle \sin 2\theta, 0, \cos 2\theta \right\rangle$. If θ were zero, such that the M6/M7 mirror combination did not raise the level of the beam, then predictably, the $\hat{\mathbf{i}}$ displacement of the input ray results in a $-\hat{\mathbf{i}}$ displacement of the output, while a $\hat{\mathbf{k}}$ input displacement results in a $\hat{\mathbf{k}}$ disaplcement at the output. In rotating the M6/M7 pair by θ about the y-axis, a field rotation of 2θ results. Because $\theta \approx 21.3°$, this puts the field at almost a $45°$ orientation.

2 Telescope Motions

Now one can ask: what happens when the telescope moves up in the altitude axis, or to the right on the sky (clockwise motion from above)? In what direction would a star image move on the field of view if such motions were executed? In this thought experiment, imagine we start with the telescope looking directly at a star (on axis). Our description of left-right motions on the sky relate to an observer standing behind the telescope looking out at the sky. Note that by describing image motions, we are adopting a convention $180°$ opposite to that describing the telescope motions.

If we move the telescope to a higher altitude, the column of starlight now comes into the telescope from below the optical axis. This directional offset is maintained after the two reflections from the primary and secondary mirrors, so that the stellar image will form on the side of the tertiary closest to the back port (where APOLLO accesses the beam). When the tertiary mirror is rotated to face the back port, this means the starlight hits the low side of the tertiary. This translates to hitting the side of the quaternary mirror that is farthest from the sky. Consequently, the beam enters the Utah window and hits M5 on the side farthest from the sky. After coming off of M5, the beam is displaced in the x-direction in the above-defined coordinate system. Passage through the $f/10$ diverging lens (L3) imparts a $+\hat{\mathbf{i}}$ vector displacement onto the beam. We have explored the consequences of this type of displacement upon striking M6 and M7 in the previous section. This move to higher altitude is known as "$+x$" when the instrument block does not yet have a defined instrument orientation angle.

If we move the telescope to the right on the sky (CW in azimuth from above), the column of starlight enters the telescope from the left, and will be displaced to the right side of the tertiary. This means the beam will strike the quaternary on the right, and will enter the Utah box displaced toward the optical bench. The lens, L3, will then produce a $-\hat{\mathbf{k}}$ deflection to the beam. This motion on the sky is known as "$+y$" when the instrument block does not yet have a defined instrument orientation angle.

Now let's establish the mapping between telescope motions and beam directions entering the receiver. The $+x$ telescope motion results in a $\hat{\mathbf{i}}$ ray displacement prior to M6, which becomes a $\langle -\cos 2\theta, 0, \sin 2\theta \rangle$ displacement entering into the receiver. So the light approaches the receiver traveling to the left and upward, from the receiver's perspective, looking out. To the receiver, this ray appears to come from the lower-right quadrant. Here, "up" means away from the optical bench.

A $+y$ telescope motion imparts a $-\hat{\mathbf{k}}$ directional displacement to the beam as it heads for M6, and this turns into a $\langle -\sin 2\theta, 0, -\cos 2\theta \rangle$ vector heading toward the receiver. So the light approaches the receiver traveling downward and to the left, again looking out from the receiver's perspective. To the receiver, this ray appears to come from the upper-right quadrant. Here, "down" means toward the optical bench.

3 Orientation of Fields

There are four relevant fields to define: the CCD camera, the upper periscope position, the lower periscope position, and the APD array. We will describe each of these, and at the end tie this in to sky coordinates.

3.1 CCD Orientation

The CCD camera receives light via reflection off of a beamsplitter at the front of the receiver (labeled BS in Figure 1). Putting yourself in the position of the CCD lens, looking at the reflection from the front of the receiver, the light resulting from a $+x$ telescope displacement comes at the CCD as if originating from a direction low and to the left.

Given the way the CCD is oriented, and the effect of the lens in front, this results in a displacement on the viewing screen high and to the right. In other words, moving the telescope in the $+x$ direction results in the star drifting toward the upper right corner of the image. Likewise, a $+y$ motion comes at the CCD from high and to the left, putting the star in the lower right corner of the CCD image. See Figure 2 for the layout.

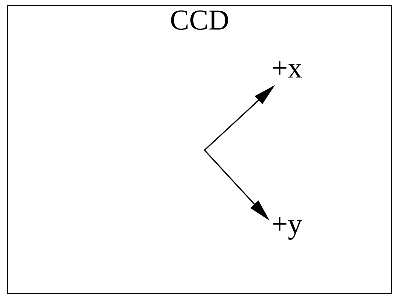

Figure 2: Motions of a star on the CCD frame resulting from telescope motions here described as $+x$ and $+y$.

3.2 Upper Periscope Orientation

A $+x$ telescope motion results in previously centered starlight now entering the receiver traveling to the left and upward. The periscope—when located in the upper position at the entrance to the receiver—catches this light directly. The light then hits a right-angle prism, directing the light into the positiv z direction in the right-handed coordinate system defined for the optical bench in Figure 1. Looking down into this beamsplitter, one would perceive the light from a $+x$ telescope motion as coming from from above and to the right. The telescope would then represent this as a point to the lower left of the crosshair. A $+y$ motion of the telescope results in light approaching the receiver traveling to the left and downward, so that the beamsplitter sees light coming in from the upper right. Now looking down into the receiver, one sees light coming from the lower-right quadrant, forming an image on the telescope to the upper-left of the crosshair. Figure 3 depicts this geometry.

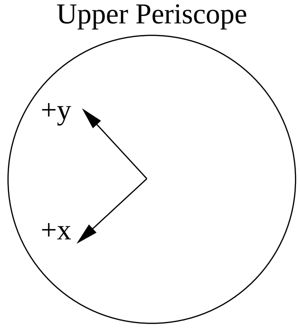

Figure 3: Motions of a star as seen in the alignment periscope in the upper position resulting from telescope motions here described as $+x$ and $+y$.

3.3 Lower Periscope Orientation

We can quickly produce the orientation of the lower periscope field by noting that the spatial filter imposes a $180°$ field rotation as compared to the upper periscope field. But because the description of ray directions will be helpful in propagating to the APD, we will describe the intermediate results here. As before, a $+x$ telescope motion results in light approaching the receiver traveling to the left and upward (upward meaning away from the bench). Assuming the motion is small enough to make it through the pinhole, the resultant image at the pinhole focal plane will be to the upper-left of field center. By upper-left, we mean in the ($+z$, $-x$) directions in the optical bench coordinate system. Upper-left is as seen from behind the pinhole, looking out at the sky. A point to upper-left in the pinhole will be routed to lower-right by the second lens in the spatial filter. Thus the spatial filter reversed the ray direction by $180°$. The same trick happens in a $+y$ telescope motion: light approaches the receiver traveling to the left and downward. This forms an image at the pinhole to the lower-left of center, translating to a ray direction traveling up and to the right after the second spatial-filter lens. The result is a field orientation $180°$ from the upper-periscope field orientation, as shown in Figure 4.

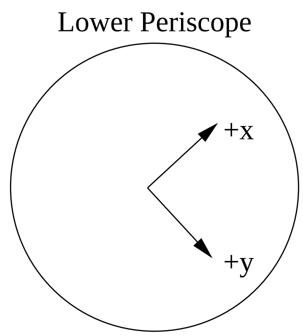

Figure 4: Motions of a star as seen in the alignment periscope in the lower position resulting from telescope motions here described as $+x$ and $+y$.

3.4 APD Array Orientation

Continuing the ray path to the APD, we know from the previous section that $+x$ and $+y$ telescope motions result in rays traveling to the lower-right and upper-right, respectively. In terms of the optical bench coordinate system, these rays are traveling toward ($+x$ and $-z$) and ($+x$ and $+z$), respectively. This ray direction is preserved through the final focusing lens, so that these two rays arrive at the APD (or lenslet array, more precisely) displaced to the lower-right and upper-left. If we now re-orient our view, and look at the front of the APD chip, we see something like the geometry depicted in Figure 5.

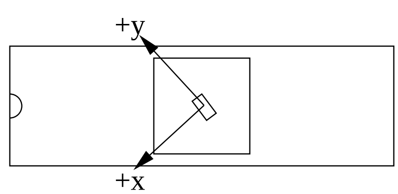

Figure 5: Motions of a star as seen looking at the face of the APD chip, resulting from telescope motions here described as $+x$ and $+y$. Up in the figure is away from the optical bench ($+z$ direction), and left in the figure is away from the laser ($+x$ direction).

The APD array is itself oriented at a funny angle relative to the chip. As seen in Figure 5, the array is rotated about $53°$ clockwise. As depicted here, element 1 of the array is in the left corner, 4 is in the upper corner, 13 is the lower corner, and 16 is the right-most corner. Because we labled the APD array looking at the face of it (rather than as seen from behind) together with the fact that we display the 4×4 grid in this same, front-facing orientation, we can go directly from Figure 5 to Figure 6, which depicts the direction of image motion on the dispayed 4×4 grid, with corner pixels labled.

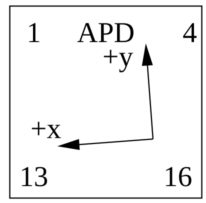

Figure 6: Motions of a star as seen on the APD array resulting from telescope motions here described as $+x$ and $+y$. By conicidence, the orientation is nearly aligned with the telescope axes.

4 Relative Orientations of Sky, CCD, and APD

Now that we have established image motion directions on the relevant focal planes, we can tie the fields together. Only the connection between CCD and APD are really important, so we provide a CCD-centric view of the APD orientation, plus an APD-centric view of the CCD orientation (Figure 7). We are lucky that these fields are only rotated with respect to each other, and not reflected. Even though the CCD path experiences an even number of reflections, and the APD an odd number, the manner in which we arbitrarily decided to label and display the APD elements introduced an effective reflection, since we labled looking at the front of the detector. Conventionally, detectors are labeled looking at the back, so that the recorded image is not needlesly reflected.

Figure 7: Orientations of the APD in the CCD frame, and of the CCD in the APD frame. The text is oriented appropriately, so that it would be legible with no rotations or reflections on the display of each device.

We can also establish orientations of the CCD and APD relative to the sky. Again, we are lucky that there are no reflections in these fields. Figure 8 shows a view of the sky as if you are standing behind the telescope looking out in the direction the telescope is pointing. The horizon is down, and the right side of the image is what you see to your right. In other words, it is a sensibly oriented figure. The CCD and APD orientations are represented with the lettering indicating the orientation. The letters would appear upright and normal when looking at the associated display.

5 Nudge Directions on the CCD and APD

Of practical importance when driving the system is the object motion resulting from various nudges to the telescope or optics. There are three ways in which the APOLLO pointing/alignment is adjusted during operation:

- Boresight offsets: generally affected by the telescope operator when refining the telescope pointing, usually while watching the effect on the CCD image. Nomenclature is the $+x$ and $+y$ motions used throughout this document.
- Receiver (RX) offsets: steers the pointing of the receiver relative to the telescope. If it is thought the receiver/CCD is pointing at the correct location already, a compensated "beam offset" motion is available that

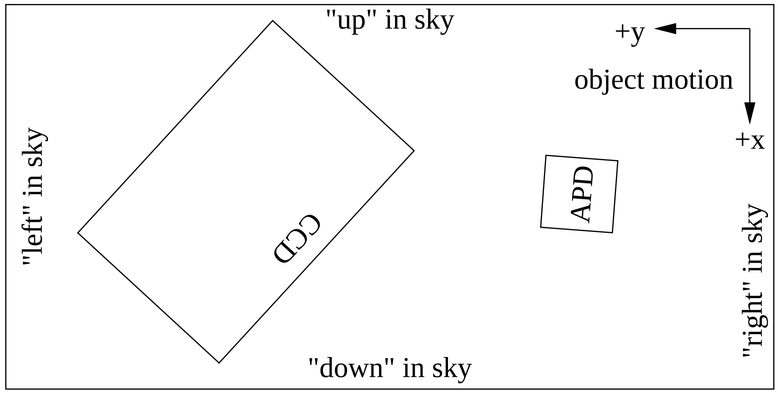

Figure 8: Orientation of the CCD and APD fields on the sky. Since we worked in the context of image motion resulting from the $+x$ and $+y$ telescope motions, and these corresponded to moving the telescope to higher altitudes and to the right (CW from above), the indicated directions are opposite this, again depicting the resulting apparent image motion.

moves both receiver offset and the telescope in tandem to produce an effective motion of the laser beam pointing. In either compensated or uncompensated modes, the receiver offset coordinates are the same, and are called ±rxx and ±rxy. The APOLLO TUI window controls these motions with up/down, left/right buttons.

- Guide offsets: used to raster or adjust the telescope pointing during a run. The coordinate system is azimuth/elevation, but with a sign flip from the $+x$ and $+y$ boresight directions. The APOLLO TUI window controls these motions with up/down, left/right buttons.

The *motion of an object* under each of these types of offsets is shown in both the CCD and APD frames in Figures 9 and 10, respectively.

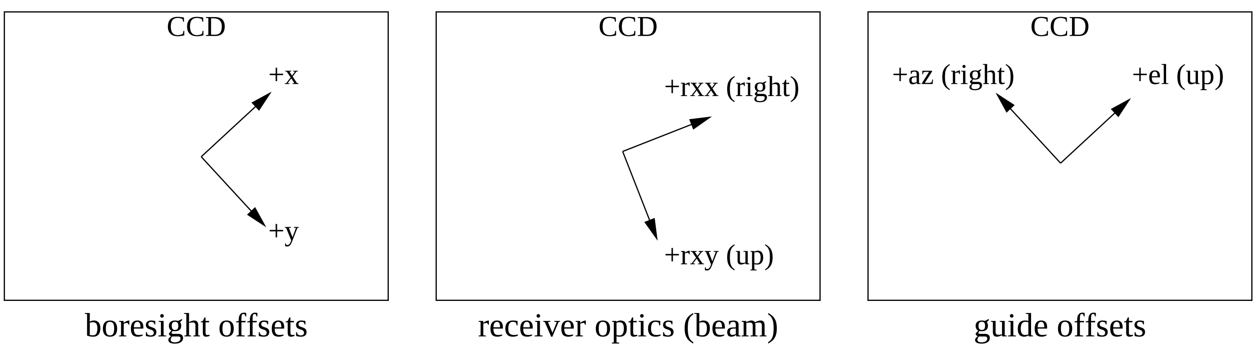

Figure 9: The angles of user offsets as seen on the CCD frame. The motion is *that of the object* after such an offset.

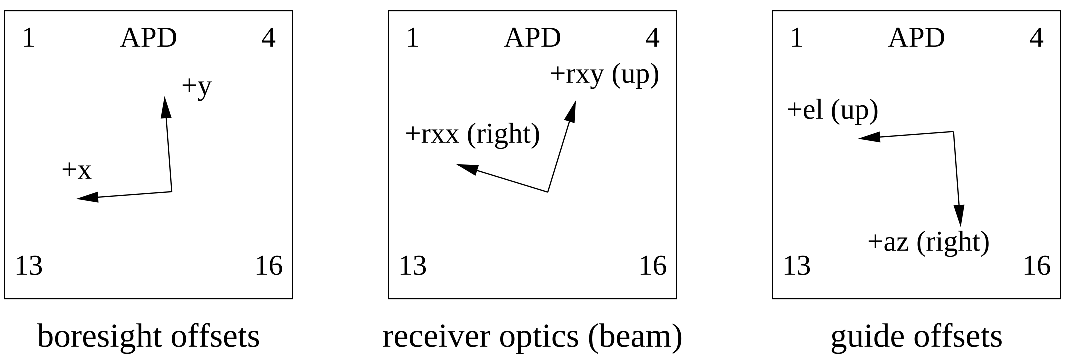

Figure 10: The angles of user offsets as seen on the APD frame. The motion is *that of the object* after such an offset.