DCS Coordinate Systems

File: 3.5.6 (KSDs), Library KSD Binder, Summit KSD Binder

Circulation: Observing Assistants, Instrument Specialists, Instrument PIs, Software Coordination Committee, Software Group, Technical Managers

Table of Contents

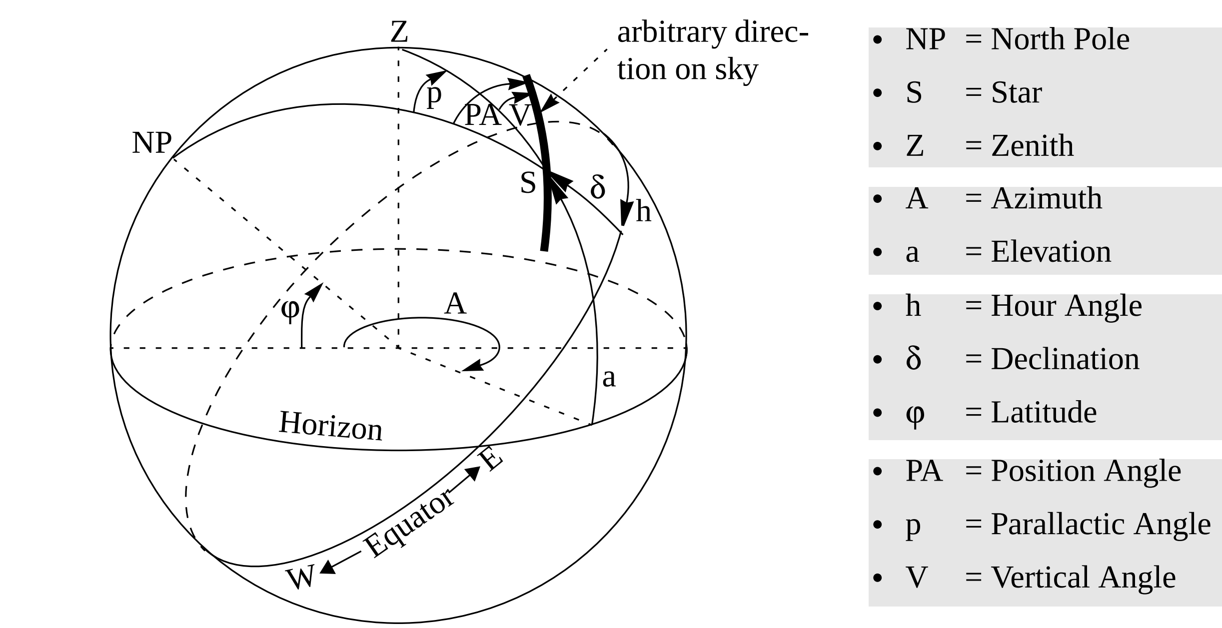
1.0 Introduction

This document defines the various DCS coordinate systems, illustrates the relationships between them (via diagrams and by reference to the corresponding DCS keywords), and presents pictures of the various focal-station / instrument combinations. It also includes sections on how to determine rotator user angles from astronomer-supplied position angles, and on NIRC / chopper relative orientations.

2.0 Coordinate Systems

Figure 1 illustrates the major telescope coordinate systems, presented as a 3D view from outside of the celestial sphere. It provides the context for the other coordinate system diagrams in this document, which are 2D representations of the view from inside the sphere and which serve only to indicate the relative orientations of the various coordinate systems.

FIGURE 1. Coordinate systems on the celestial sphere[a]



a. Adapted from Figure 1 of *UC TMT REPORT No. 49, "Geometrical Relations for an Altitude-Azimuth Telescope"*

Figure 1 indicates (as a bold line) an arbitrary direction on the sky which maps on to a guider or instrument detector column or slit which is to be kept at a fixed orientation relative to the North

Pole (NP) or the Zenith (Z). The Figure illustrates the definitions of the parallactic (p), position (PA) and vertical (V) angles.

Figure 2 uses the same terminology as Figure 1 but this time shows the view looking out from within (so there is a handedness flip) and orients North up (with East to the left). It only shows directions and is now 2D (think of it as showing the various directions at the star S). Figure 2 also illustrates some differences between Figure 1 terminology and that of the rest of the document.

FIGURE 2. Coordinate systems viewed from inside the celestial sphere

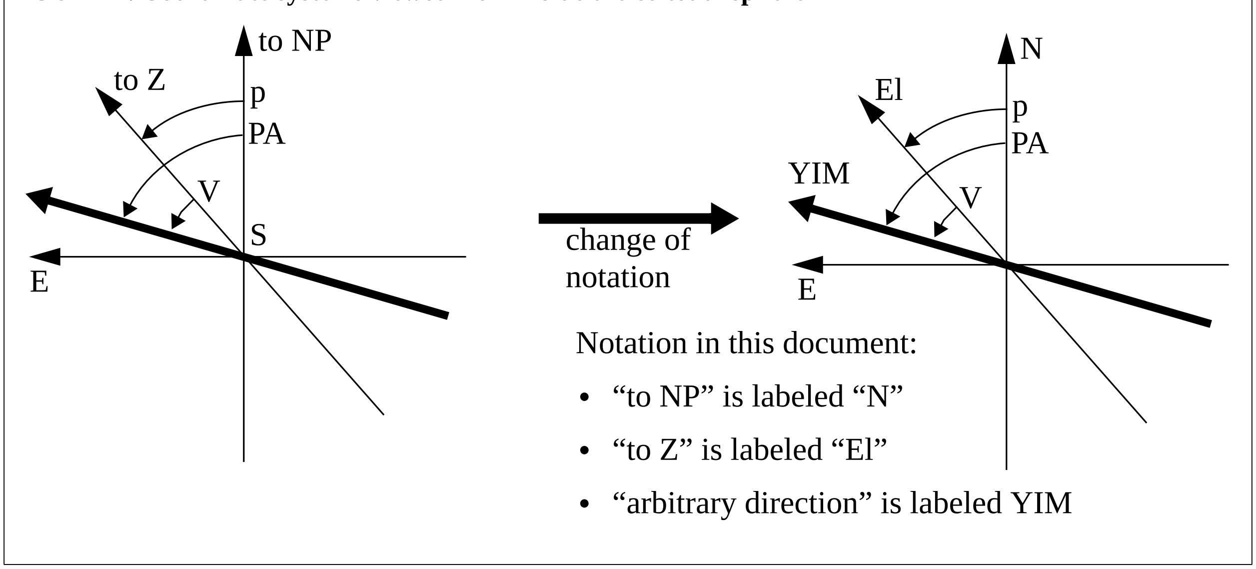


Figure 3 illustrates the coordinate systems which are relevant to this document. It is valid for both Keck telescopes and for all but Nasmyth focal-stations (these differ because there is an extra elevation angle dependence due to the fact that the instrument is mounted off the telescope; see Figure 4 on page 7 and Figure 5 on page 7).

Note how Figure 3 is consistent with Figure 2: it has just been rotated to make YIM (the pointing origin Y axis; to be defined) point upwards. TV and instrument coordinate systems are shown together because they are handled in identical ways.

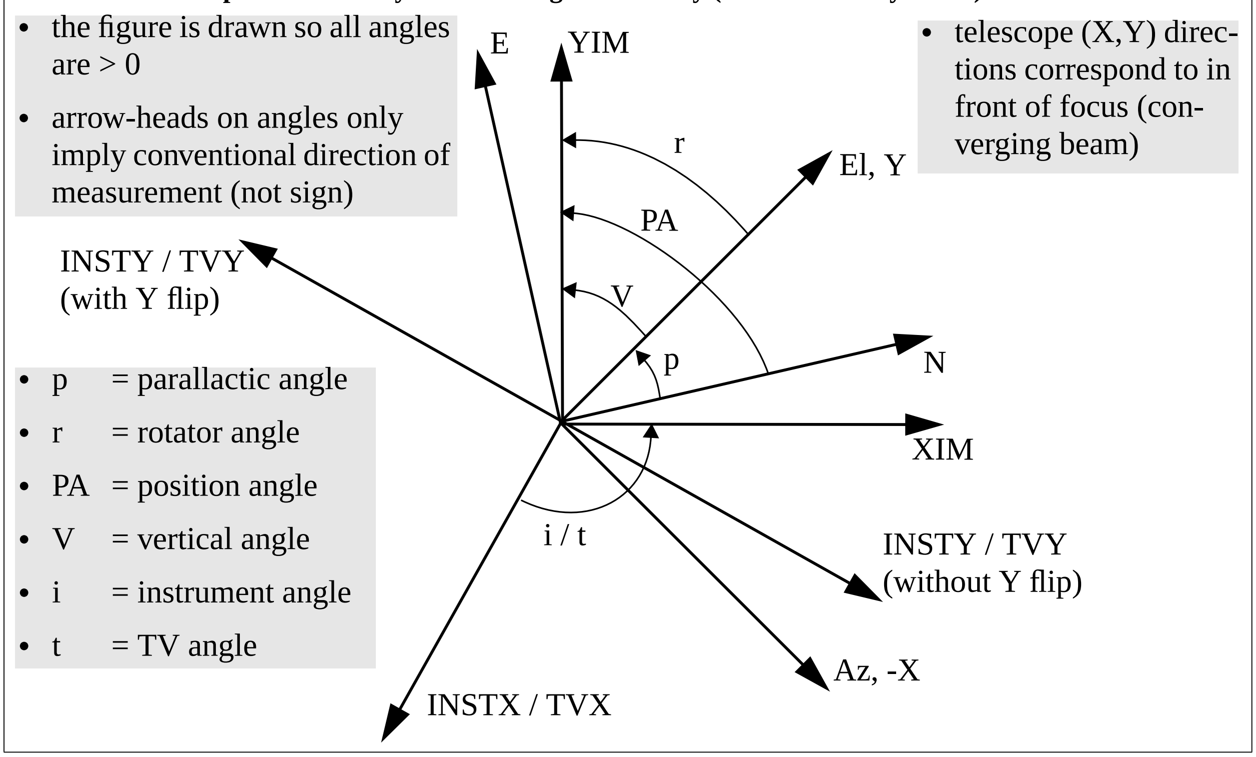
2.1 Telescope Coordinate System

This is a right-handed 3D coordinate system fixed in the telescope such that when the telescope is at the horizon, Y is pointing into the ground, Z always points along the telescope optical axis towards the sky, and X completes the right-handed triple. The origin of this coordinate system is the intersection of the (vertical) azimuth axis of rotation and the (horizontal, rotating) elevation axis of rotation. This point should lie on the surface of the tertiary mirror.

This is the coordinate system in which telescope surveys are carried out. It is also the coordinate system in which ACS mirror positions are defined. Its X and Y are related to the (Az,El) coordinate system in that, ignoring small telescope misalignment errors, the telescope X axis points in the positive azimuth direction and the telescope Y axis points in the negative elevation direction.

Figure 3 ignores these small errors and marks one axis as Az and -X and another axis as El and Y (the signs have changed from the previous paragraph; read on!). What this means is that

FIGURE 3. Telescope coordinate systems looking towards sky (excludes Nasmyth foci)



- in the focal plane, the (Az,El) axes point towards those parts of the field which are at higher azimuth and elevation respectively
- *in front of focus* (i.e. in the converging beam between the primary mirror and the focal plane), the (X,Y) axes correspond to the section of the primary from which the light in the beam has come

In the focal plane it is not possible to ascribe meaning to the (X,Y) coordinate system, and on the other side of focus the (X,Y) directions change sign.

2.2 (Az,El) Coordinate System

This 2D coordinate system corresponds to the telescope azimuth and elevation axes. As noted in the previous section

- in the focal plane, the (Az,El) axes point towards those parts of the field which are at higher azimuth and elevation respectively

These axes should not be confused with the (Az,El) axes *of rotation*, which are the axes about which the telescope rotates. The Az axis of rotation is vertical and the El axis of rotation is horizontal and rotates as the telescope Az changes. If this document ever needs to refer to the axes of rotation, it will say so!

As can be seen from Figure 3, the (Az,El) coordinate system is right-handed when looking towards the sky.

The (Az,El) coordinate system is really a spherical system. This document refers loosely to (Az,El) as tangent plane Cartesian coordinates. In the tangent plane coordinates, a given change in a star's El corresponds to the same change in the telescope's El. However, a given change in a star's Az corresponds to a change in the telescope's Az which is greater by a factor of 1/cos(El) (the details aren't important, but to see what is happening, consider a star near the zenith: a large change in telescope Az hardly moves the star).

For the purposes of this document, no distinction is drawn between the telescope (Az,El) coordinate system and the astrometric (Az,El) coordinate system. If the telescope were perfect, these two coordinate systems would be identical. However, the telescope axes are not precisely orthogonal to each other and the telescope is not perfectly horizontal. These errors are accounted for by the telescope pointing model. One practical result of the errors is that, while the parallactic angle (PARANG keyword) is the correct angle to rotate between North and the astrometric positive Elevation axis (astrometric vertical), it is not quite the correct angle to rotate between North and the telescope positive Elevation axis.

2.3 (RA,Dec) Coordinate System

This 2D coordinate system corresponds to the celestial coordinate system, whose axes are defined in terms of the earth (Right Ascension is analogous to Longitude and Declination is analogous to Latitude). The same comments about spherical and tangent plane coordinate systems apply here, reading Dec for El and RA for Az.

As can be seen from Figure 3, the (RA,Dec) coordinate system is left-handed when looking towards the sky. The directions are conventionally labeled "E" (for "East", the direction of increasing RA) and "N" (for "North", the direction of increasing Dec).

2.4 Pointing Origin Coordinate System

This is a 2D coordinate system conceptually inscribed on the instrument module in the focal plane. Each focal-station has such a coordinate system, although it is currently explicitly used only at those that have image rotators. As can be seen from Figure 3, the pointing origin coordinate system is right-handed when looking towards the sky.

For focal-stations with rotators, the origin of the coordinate system is defined as the point at which the rotator's rotation axis intersects the focal plane, and the Y axis is parallel to the TV Y axis. The rotator zero point is chosen so that at zero rotator angle (and, for Nasmyth foci, elevation angle) the pointing origin Y axis coincides with the telescope elevation axis.

For focal-stations without rotators, pointing origin offsets are indistinguishable from collimation corrections and the choice of coordinate system origin is arbitrary. It will typically be the center of the guider detector.

(X,Y) positions are measured in mm (to underline the fact that a pointing origin is a position in the focal plane). Pointing origins are identified by name and the REF pointing origin is always the center of the guider (for LRIS, which has two guiders, it is the center of the slit-viewing guider). The notation (XIM,YIM) refers to a point in the pointing origin coordinate system ("IM" for "IMage plane").

The term "pointing origin" is widely used but is nevertheless the source of much confusion: the name does not imply what the coordinate system is used for. Accordingly, while the name is being retained, user software will increasingly use the synonymous and more descriptive term “detector location”.

2.5 TV Coordinate System

The TV coordinate system is defined to be a conventional Cartesian coordinate system (i.e., origin at bottom left-hand corner) referred to the guider display. The transformation from TV coordinates to pointing origin coordinates consists of an optional Y flip followed by a rotation. Given that the pointing origin Y axis is always parallel to the TV Y axis, the rotation angle is always either 0 or 180 deg (Figure 3 illustrates an arbitrary angle in order to reduce confusion in drawing and labeling axes).

LRIS has two guiders, which happen to be very nearly parallel to each other. The slit-viewing guider is used for defining the TV coordinate system (and we have not yet accurately measured the moveable guider’s orientation).

2.6 Instrument Coordinate System

The instrument coordinate system’s Y axis is whatever is most appropriate to the users of the instrument in question (usually either a slit or the instrument detector’s Y axis). The transformation from instrument coordinates to pointing origin coordinates consists of an optional Y flip followed by a rotation (see Figure 11, “f/25, Guider, NIRC and Chopper Orientations,” on page 16, for an example).

Luckily, instrument slits seem usually to be vertical on instrument detector displays, meaning that the instrument coordinate system origin can usually be placed at the bottom left-hand corner of the display (this is the case for LRIS and NIRC, maybe also for HIRES and LWS?), which is nicely consistent with the TV coordinate system.

2.7 Generalization to Include All Focal-stations

Figure 3 excluded Nasmyth foci, which have an extra elevation angle dependence owing to the fact that the instrument is not mounted on the telescope. The sign of this dependence is opposite at the two Nasmyth foci. This means that, while individual pictures are useful for promotion of physical understanding, software coordinate transformations can apply to all focal-stations if the sign of the elevation dependence is set as follows:

- -1 left Nasmyth
- +1 right Nasmyth
- 0 otherwise

Figure 4 and Figure 5 are versions of Figure 3 for Left and Right Nasmyth foci respectively. They differ from Figure 3 only in that a new “local vertical” line has been introduced, from which the rotator and elevation angles are measured.

FIGURE 4. Telescope coordinate systems looking towards sky (Left Nasmyth focus)

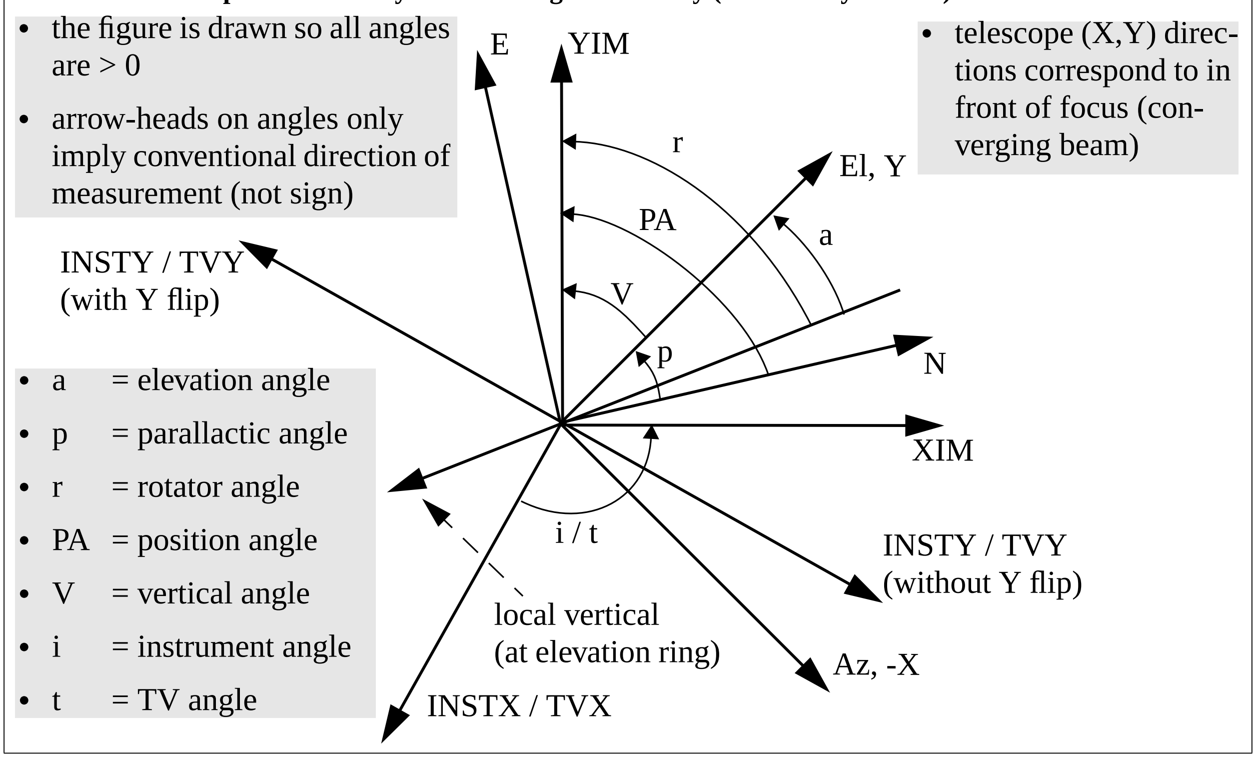
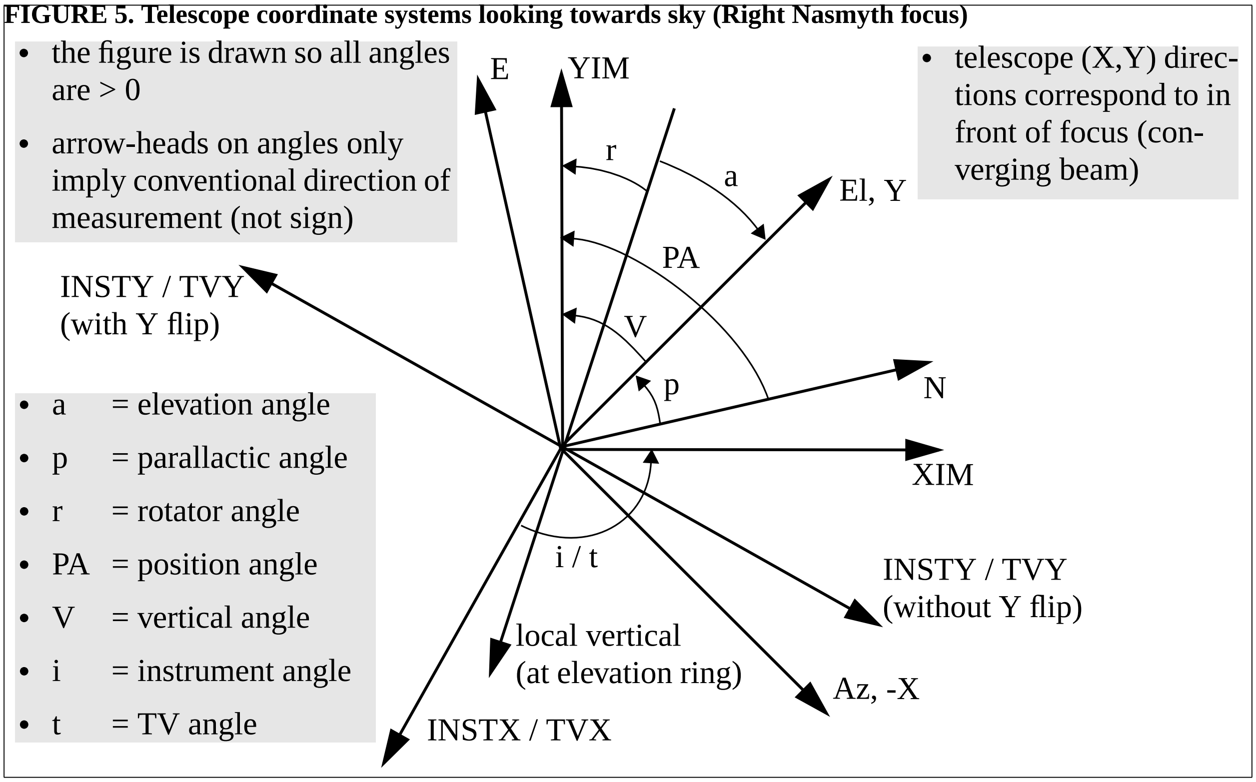


FIGURE 5. Telescope coordinate systems looking towards sky (Right Nasmyth focus)



3.0 Coordinate Transformations

Figure 3, Figure 4 and Figure 5 can be used to write down formulae to be used for the following purposes (these are not the only possibilities; they are those needed by the DCS during normal operation):

- generation of rotator angle demands as a function of rotator tracking mode
- generation of (RA,Dec) and (Az,El) compass roses oriented correctly for the guider or instrument display
- conversion of user-requested (INSTX,INSTY), (TVX, TVY), (XIM,YIM) or (Az,El) offsets to (RA,Dec) offsets
- conversion of guider (XIM,YIM) offsets to (Az,El) or (RA,Dec) offsets for the purpose of guiding or guider-based offsetting

Subsequent sections describe each of these in some detail and specify which DCS keywords correspond to the various angles and modes.

3.1 Rotator Control

A rotator can be in any one of three tracking modes:

- position angle mode, in which the YIM axis is maintained at a fixed “position angle” (PA) relative to North,
- vertical angle mode, in which the YIM axis is maintained at a fixed “vertical angle” (V) relative to the vertical (Elevation axis), and
- stationary mode, in which the rotator is stationary at a fixed “rotator angle” (r).

Section 4.1, “Position Angles and Rotator User Angles,” on page 14 discusses position angles in more detail, taking NIRC and LRIS as examples.

The rotator therefore requires just two parameters, a “user angle” (ROTDEST keyword) and a tracking mode” (ROTMODE keyword). The interpretation of ROTDEST is a function of the mode. Referring to Figure 5, it is clear that at Right Nasmyth the following are always true:

- PA = p + a + r
- V = a + r

Therefore, taking each tracking mode in turn:

TABLE 1. User and rotator angles for rotator tracking modes (Right Nasmyth only)

tracking mode	user angle (UA)	rotator angle (r)
position angle	PA	UA - p - a
vertical angle	V	UA - a
stationary	r	UA

It should also be clear that at Left Nasmyth the sign of elevation (a) has to be changed and that at all other focal stations elevation is simply ignored. Thus we have:

TABLE 2. User and rotator angles for rotator tracking modes (all focal-stations)

tracking mode	user angle (UA)	rotator angle (r)
position angle	PA	UA - p - sign(foc)[a] * a
vertical angle	V	UA - sign(foc) * a
stationary	r	UA

a. sign(foc) is the elevation sign as a function of focal-station: +1 for Right Nasmyth, -1 for Left Nasmyth, 0 for all others.

3.2 Rotator Keywords

Six keywords are needed in order to reproduce Table 2 in the keyword world:

- EL, the elevation (a)
- FOCALSTN, the current focal-station
- PARANG, the parallactic angle (p)
- ROTDEST, the desired user angle (UA)
- ROTMODE, the rotator tracking mode
- ROTPDEST, the desired physical rotator angle (r)

Refer to *KSD/46, "Keck I DCS Keyword Manual"* and *KSD/106, "Keck II DCS Keyword Manual"* for details of these keywords.

TABLE 3. User and rotator angles for rotator tracking modes (all focal-stations; keyword version)

tracking mode	user angle (ROTDEST)	rotator angle (ROTPDEST)[a]
position angle	PA	ROTDEST - PARANG - sign(FOCALSTN)[b] * EL
vertical angle	V	ROTDEST - sign(FOCALSTN) * EL
stationary	r	ROTDEST

a. Note that these relationships do not hold precisely when EL is the telescope elevation (refer to Section 2.2 on page 4). We could and should define another keyword, which would be very similar to PARANG but which would allow the relationships to be precisely correct.

b. sign(FOCALSTN) is the elevation sign as a function of focal-station: +1 for Right Nasmyth, -1 for Left Nasmyth, 0 for all others.

Many will be familiar with two further rotator keywords:

- ROTPOSN, the achieved user angle (UA)
- ROTPPOSN, the achieved physical rotator angle (r)

When the rotator is tracking, the "POSN" keywords will have values which are close to the "DEST" keywords.

3.2.1 Rotator zero and calibration angles

Section 2.4, “Pointing Origin Coordinate System,” on page 5 refers to the “rotator zero point” being chosen so that at zero rotator angle the pointing origin Y axis coincides with the telescope elevation axis. The rotator zero point (ROTZERO keyword) is defined as the value which, during a full initialization, is loaded into the rotator encoder when the home switch is encountered.

ROTZERO is not convenient to use, because the effect of a change can be seen only by performing a full rotator re-initialization. A more convenient way to get the zero point right in the first place is to use the rotator calibration angle (ROTCALAN keyword) which is simply a value which is added to ROTDEST (and subtracted from ROTPOSN).

Once the zero point is correct, ROTCALAN can be absorbed into ROTZERO. A positive ROTCALAN corresponds to a negative ROTZERO adjustment for all but the Bent Cassegrain rotators (where the physical rotator angle is measured in the opposite direction on the sky), for which it is a positive ROTZERO adjustment. Once this has been done, further fine tuning may slightly change ROTCALAN. Such small changes need not be absorbed into ROTZERO (large changes must be absorbed so that guider corrections, which make use of ROTPPOSN, will be in the correct (Az,El) direction).

3.2.2 Rotator reference angle

The rotator reference angle (ROTREFAN keyword) is equivalent to ROTCALAN in that it is (currently) added to ROTDEST and subtracted from ROTPOSN. However, it serves a completely different purpose: it’s to permit ROTDEST and ROTPOSN to be measured relative to a zero that makes sense to the instrument user (e.g. a slit or an object/guide star vector) rather than relative to the YIM axis.

Currently, all ROTREFAN values are zero. We are discussing whether it would be better *not* automatically to apply it to ROTDEST and ROTPOSN but instead to leave that up to keyword clients. This would make the transition from the current situation (where clients apply various hard-coded instrument-specific offsets) more smooth.

Refer to Section 4.1, “Position Angles and Rotator User Angles,” on page 14 for exhaustive discussion of the above-mentioned instrument-specific offsets.

3.3 Compass Roses

A compass rose displays a (N,E) or an (Az,El) rosette close to the guider or instrument display. Consider the guider display: the TV coordinate system is defined to be a conventional (origin at bottom-left) coordinate system when looking at the guider display. Now referring to Figure 5 on page 7 (Right Nasmyth), it is clear that the anti-clockwise (clockwise if there’s a Y flip) rotation from

- the TVX axis to N = t + (90 - PA) = t + 90 - (p + a + r)
- the TVX axis to E = t + (90 - PA) + 90 = t + 180 - (p + a + r)
- the TVX axis to El = t + (90 - V) = t + 90 - (a + r)
- the TVX axis to Az = t + (90 - V) - 90 = t - (a + r)

and this defines the guider compass rose orientations as a function of TV angle, TV flip, parallactic angle, elevation angle and rotator angle (independent of rotator tracking mode). The instrument compass roses are analogous (but note that whereas the TV coordinate system is defined in relationship to the guider display, the instrument coordinate system is typically defined in relationship to a slit).

The above formulae are generalized to all focal stations using the same "sign(foc)" elevation sign that was used in the previous section.

3.4 Compass Keywords

The only new keywords are TVFLIP (whether a TV Y flip is necessary) and TVANGL (the angle referred to as "t" above, always 0 or 180).

INSTFLIP (whether an instrument Y flip is necessary) and INSTANGL (the angle referred to previously as "i") are (roughly) the instrument equivalent of TVFLIP and TVANGL. The previous section expains why the term "roughly" is used. However note that for all existing instruments the instrument coordinate system is identical to or very close to the conventional Cartesian coordinate system as viewed on the instrument display, so there is not too much of a practical problem.

We intend providing DCS keywords which contain the results of these formulae and can be used directly to drive compass roses.

3.5 Telescope Offsets

Telescope offsets can be requested in any one of the instrument, TV, (Az,El) or (RA,Dec) coordinate systems. Offsets in any of the first three systems are converted to (RA,Dec) offsets before being applied.

Figure 6 on page 12 shows a flow diagram of the conversions. This corresponds directly to the DCS offsetting code except that the issue of whether coordinates are "scaled" on the sky (which introduces cos(El) and cos(Dec) terms as mentioned in Section 2.2 on page 4) is ignored.

3.6 Offset Keywords

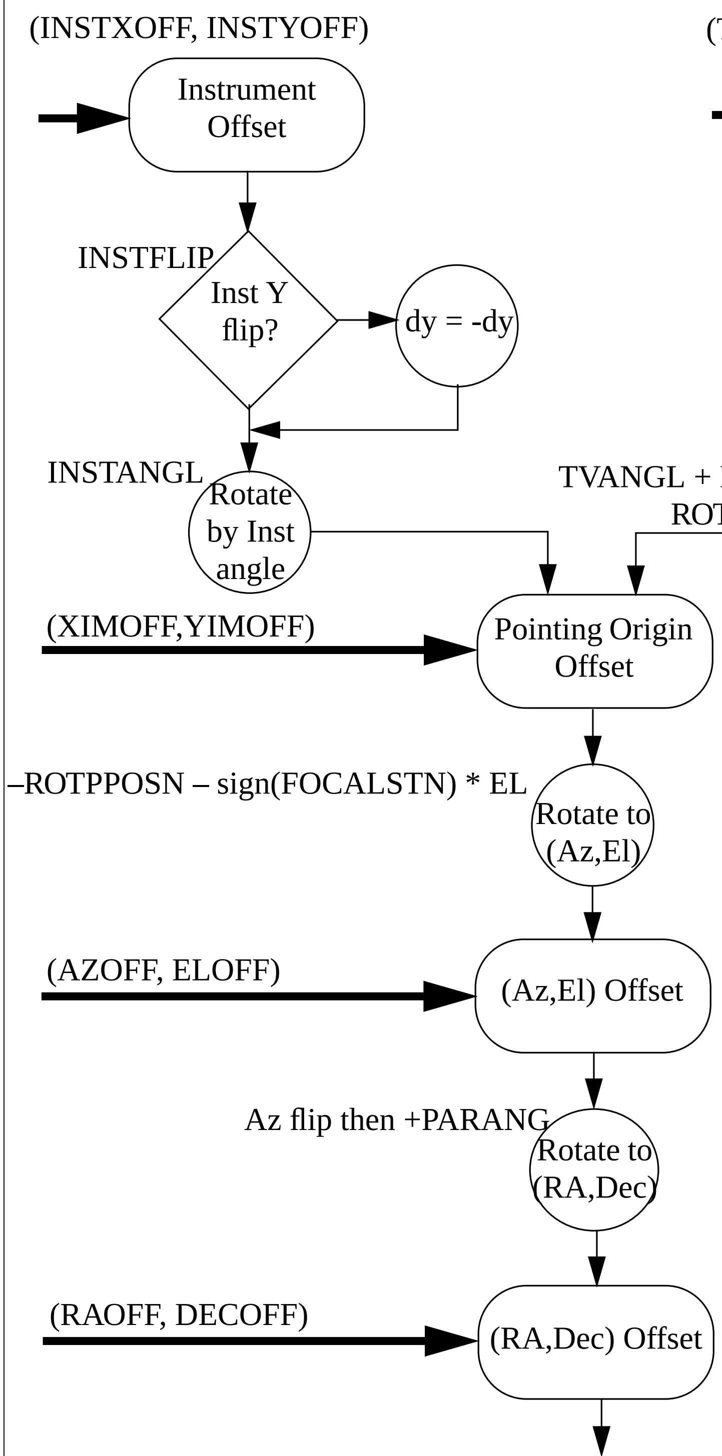
Most of the keywords involved in offsetting are illustrated in Figure 6. The keywords that actually initiate an offset (the *OFF keywords do not take immediate effect) are not shown. These are:

- REL2CURR ("relative to current"): set to 1 or TRUE to move relative to the current position (so, for example, an offset of (0,0) will do nothing; this is the most common type of offset)
- REL2BASE ("relative to base"): set to 1 or TRUE to move relative to the base position (so, for example, an offset of (0,0) will return to the base position; this type of offset is less common)
- MARK ("mark base"): set to 1 or TRUE to mark the current position as the base position
- GOTOBASE ("go to base"): set to 1 or TRUE to return to the base position

Further keywords can be read to determine the current telescope position:

- RABASE and DECBASE are the telescope base position

FIGURE 6. Telescope Offset Conversions (ignoring on-sky scaling issues)



1. Effects of on-sky scaling are ignored (by default, all offsets are on the sky, corresponding to SCALED = TRUE)
2. All rotations are positive (anti-clockwise), i.e. using the following matrix multiplication:

$$\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} dx \\ dy \end{bmatrix}$$

3. sign(FOCALSTN) is the elevation sign as a function of focal-station: +1 for Right Nasmyth, -1 for Left Nasmyth, 0 for all others
4. NOGROT indicates that the guider is pre-rotator, so there is an extra ROTPPOSN rotation to (XIM,YIM)

- RA and DEC are the telescope current position
- RAOFF and DECOFF (when read) are the “current – base” offset

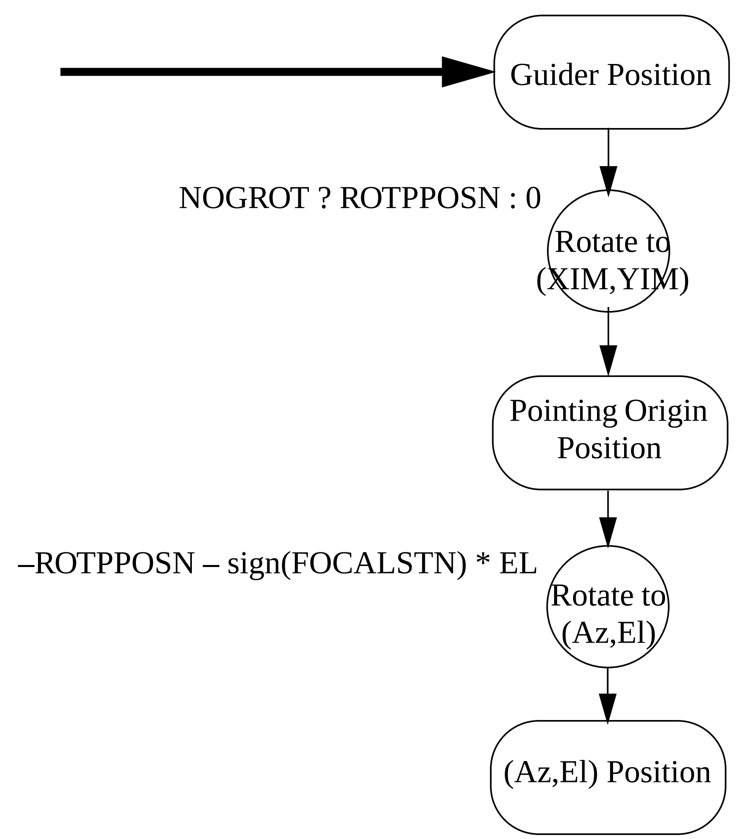
Refer to *KSD/46, “Keck I DCS Keyword Manual”* and *KSD/106, “Keck II DCS Keyword Manual”* for full details.

3.7 Guider Conversions

The guider usually generates centroids in the pointing origin coordinate system (if the guider is pre-rotator then it generates centroids in an unnamed coordinate system tied to the guider detector which has to be rotated by ROTPPOSN to become (XIM,YIM)).

These positions have to be rotated to the telescope (Az,El) coordinate system. This is illustrated in Figure 7, which is basically the central section of Figure 6.

FIGURE 7. Guider Centroid Conversions



Guider centroids can also be used for other purposes:

- to adjust collimation coefficients (e.g. the xguide CENTER command); same transformation but results stored in different variables
- to adjust pointing origin definitions (e.g. the xguide CENTER command when the “Center by adjusting pointing origin?” button has been checked); no transformation required, already in correct coordinate system
- to offset the telescope (RA,Dec) (e.g. the xguide GOTO command); same transformation, followed by Az flip and PARANG rotation to (RA,Dec) (see Figure 6)

3.8 Guider Keywords

The current DCS keyword library has some guider keywords, mostly related to guider performance. There are no keywords for controlling guider operation.

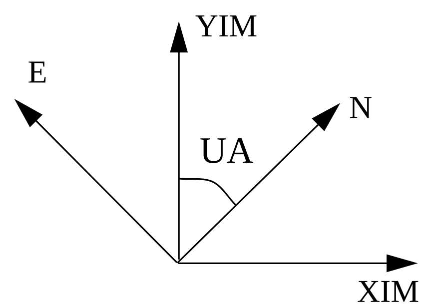
4.0 Further Discussion

This section contains more detailed discussion of some areas which were glossed over in the previous section.

4.1 Position Angles and Rotator User Angles

When in position angle mode, the rotator remains at a fixed orientation on the sky. This orientation is indicated to the DCS by the "user angle" (ROTDEST), which is the angle, measured North through East, between North and the pointing origin Y (YIM) axis. See Figure 8 on page 14.

FIGURE 8. Definition of User Angle



UA is the user angle, which is the position angle of the YIM axis.

An astronomer will think of the "position angle" (PA) as the angle, measured North through East, between North and some vector of interest to him or her. This vector of interest may be a column or slit on a science detector, or it may be the line joining a science star to a guide star. In the example above, we see that if the vector of interest is the YIM axis, then the DCS' user angle (UA) is the same as the astronomer's position angle.

4.1.1 Vector of interest is at a fixed direction on the science detector

Consider the case where the vector of interest is at a fixed direction on the science detector (e.g. a column or a slit). Usually the instrument coordinate system will be defined so that its Y (INSTY) axis is parallel with this vector of interest (both NIRC and LRIS define INSTANGL so that the INSTY axis is parallel with their columns).

Figure 9, which is modified from Figure 3 (which applies to both NIRC and LRIS), shows that the user angle (ROTDEST) to achieve the desired orientation is "PA + INSTANGL".

The sky and facsum programs collaborate to operate in this mode for LRIS and HIRES. sky subtracts (LRIS) or adds (HIRES) 90 deg from the astronomer's PA when calculating ROTDEST and facsum restores what the user input. By the above, this is consistent with the LRIS INSTANGL of -90 deg (the HIRES INSTANGL hasn't been set).

4.1.2 Vector of interest is science star to guide star vector

Consider the case where the position angle of a guide star relative to a science star has been specified (this is a common mode with the f/25 offset guider where guide stars are likely to be scarce and where the rotational degree of freedom will often have to be sacrificed in the interests of guiding).

FIGURE 9. Definition of Position Angle (instrument column mode)

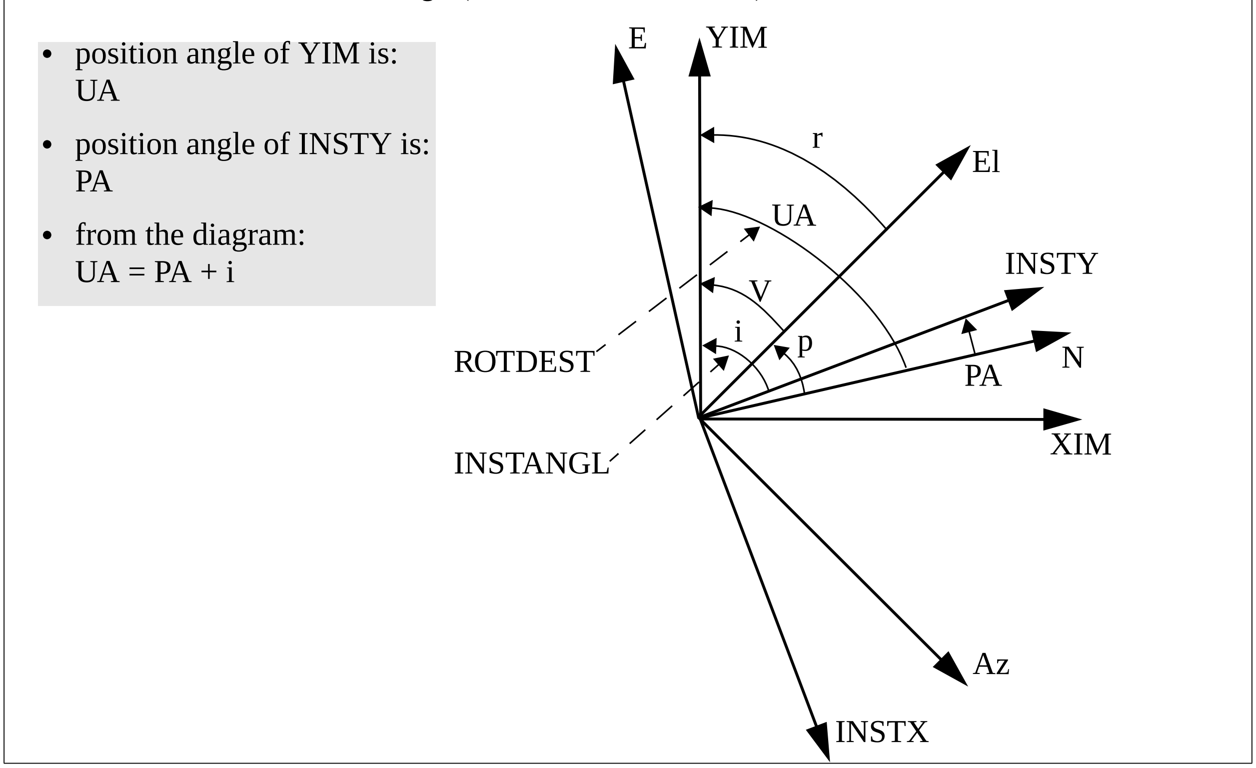


FIGURE 10. Definition of Position Angle (guide star mode)

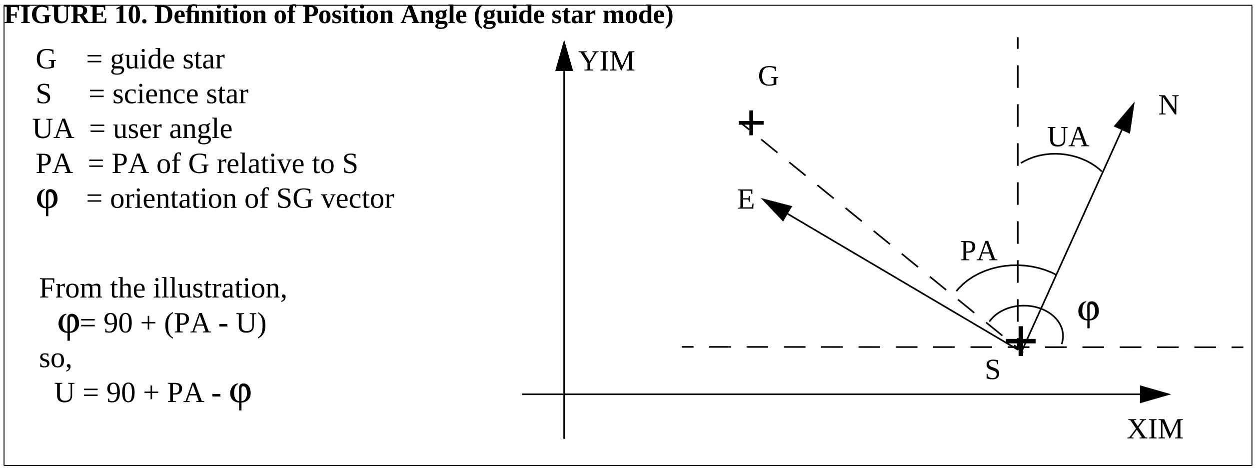


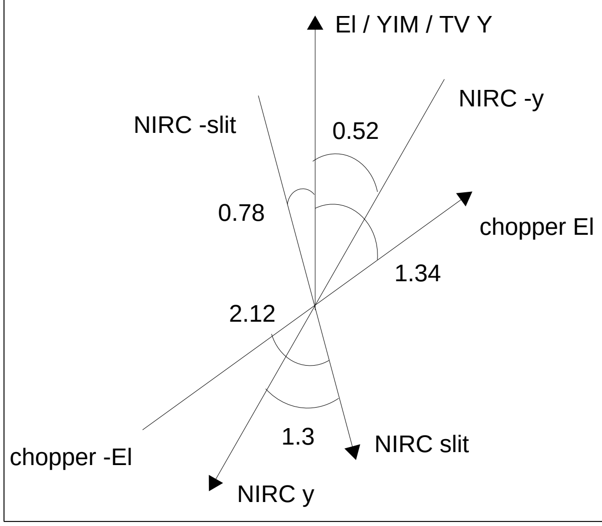
Figure 10 illustrates the relationship between the position angle (PA), the orientation of the science star to guide star vector (in the pointing origin coordinate system) φ and the resultant user angle (UA).

φ is simply calculated from a knowledge of the pointing origins. Taking NIRC as an example (Figure 13 on page 21), the NIRC pointing origin is (-2.4, 58.8) and the REF (guider) pointing origin is (-366.4,-10.2). Therefore, φ is atan2(-10.2-58.8,-366.4+2.4) = atan2(-69.0,-364.0) = 190.73 deg. Thus, for NIRC, UA = 90 + PA - 190.73, or UA = ΠA - 100.73. U = ΠA - 100 is fine for practical purposes. If the resulting UA will cause the rotator to drive into a limit, 360 deg must be added to it or subtracted from it as appropriate.

4.2 f/25, Guider, NIRC and Chopper Orientations

There has been some confusion as to the orientation of the f/25 guider, the NIRC detector and the chopper. Figure 11 on page 16 is the current best estimate. Note that this is consistent with

FIGURE 11. f/25, Guider, NIRC and Chopper Orientations



DATA SOURCES

??????: lab tests show angle between NIRC Y axis and slit is 1.3

940127: angle between chopper Elevation axis and NIRC slit measured as 2.12

940223: elevation offsets at rotator angle zero measured on NIRC give angle between TV Y and NIRC -y of 0.52

Note: illustration refers to rotator angle = 0

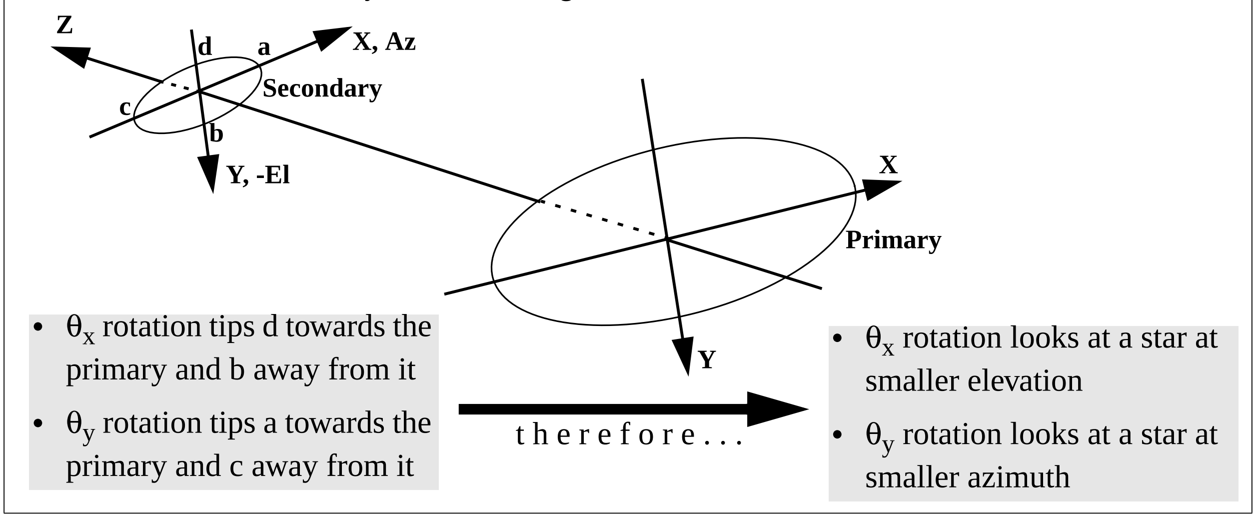
Figure 13 on page 21.

It should also be noted that the f/25 rotator zero point was determined to be in error by 1.2 deg at a recent LWS run. The new zero point was used for a subsequent NIRC run, as a result of which the “2.12” of Figure 11 was observed to change to “0.9”. Given that the “0.52” was measured using NIRC and the guider, a rotator zero point change should not have affected it. However, NIRC offsetting was very unreliable and the old rotator zero point has been restored for NIRC pending further investigation.

4.3 Effect of Secondary Tilts on Pointing

Secondary tilts are measured as conventional anti-clockwise rotations about the telescope coordinate system (Section 2.1) X and Y axes. Figure 12 illustrates the geometry and (I hope) clarifies the relationship between tilts and (Az,El).

FIGURE 12. Effect of Secondary Tilts on Pointing



The relationship between the magnitude of the secondary tilt and the resulting pointing offset is a function of which secondary is in use. *UC TMT REPORT No. 55, “Formulae Relevant to the Optical Performance of Telescopes”* quotes the relevant formulae:

$$e = \text{back focal distance (positive behind mirror)}$$

$$= \begin{cases} 2.5m & \text{(f/15)} \\ -4.538m & \text{(f/25)} \\ 2.5m & \text{(f/40)} \end{cases}$$

$$f = \text{final focal length}$$

$$= \begin{cases} 149.583m & \text{(f/15)} \\ 250.000m & \text{(f/25)} \\ 400.000m & \text{(f/40)} \end{cases}$$

$$f_1 = \text{primary focal length}$$

$$= 17.487m$$

$$\Delta = e / f_1$$

$$= \begin{cases} 0.1430 & \text{(f/15)} \\ -0.2595 & \text{(f/25)} \\ 0.1430 & \text{(f/40)} \end{cases}$$

$$m = \text{magnification by secondary} = f / f_1$$

$$= \begin{cases} 8.5540 & \text{(f/15)} \\ 14.2963 & \text{(f/25)} \\ 22.8741 & \text{(f/40)} \end{cases}$$

$$\frac{\text{image motion}}{\text{angular tilt of secondary}} = 2 \cdot \frac{1 + \Delta}{m + 1}$$

$$= \begin{cases} 0.2393 & \text{(f/15)} \\ 0.0968 & \text{(f/25)} \\ 0.0958 & \text{(f/40)} \end{cases}$$

4.4 Physical Orientation of Modules at Specified Rotator Angles

The focal-station pictures in Section A do not show the telescope XYZ coordinate system. This is partly to minimize clutter and partly to avoid confusion between

- directions on the primary mirror (which flip as you drive through focus)

- directions in the focal plane (which are always X = Az, Y = -El, Z = towards sky; also see Section 2.1 on page 3)

This latter piece of information allows determination of the module orientation as a function of rotator angle. For example, referring to Figure 13 on page 21 (f/25), at rotator angle zero, X = Az points along the positive XIM axis and Y = -El points along the negative YIM axis. As the rotator angle increases, (Az,El) rotates clockwise relative to (XIM,YIM) (which are fixed in the module), so the module rotates anti-clockwise relative to the telescope coordinate system.

5.0 Bibliography

1. UC TMT REPORT No. 49, “Geometrical Relations for an Altitude-Azimuth Telescope”
2. UC TMT REPORT No. 55, “Formulae Relevant to the Optical Performance of Telescopes”
3. KSD/46, “Keck I DCS Keyword Manual”
4. KSD/106, “Keck II DCS Keyword Manual”

6.0 Changes to this Document

- Version 1 was issued in June 1993.
- Version 2 was issued in August 1993.
- Version 3 was issued in a draft form to a reduced audience in January 1994. It was the first version issued as a KSD and also flipped the pointing origin Y axis in the pictures so that most pictures have the conventional sky orientation. It added a section on how to determine rotator user angles from astronomer-supplied position angles.
- Version 4 was issued in August 1994. It contains updated values for pointing origins and new sections on coordinate systems and f/25 guider, NIRC and chopper orientations.
- Version 5 was issued in November 1996. It was converted to Frame Maker and underwent a major overhaul with several new explanatory sections and new LWS and LRIS pointing origins.
- Version 6 was also issued in November 1996. No content changes were made, only layout changes to improve the quality of the WWW version of the document.
- Version 7 was issued in December 1997. It fixed various minor typos, cut out all mention of the parallactic angle sign error in pre-retrofit DCS versions, added a discussion of rotator zero, calibration and reference angles, updated the image motion formulae to include f/40, and added an initial version of an f/40 visitor instrument port picture.
- Version 8 was issued in February 1999. It fixed various minor typos, showed the different orientations of the two SSC cameras, and introduced the initial version of a Left Nasmyth AO picture.
- Version 9 was issued in March 1999. It removed all references to differences between Keck I and Keck II (a hangover from before the Keck I EPICS retrofit), added a proper LNAS AO picture and added visitor instruments to the RBC2 picture.

- Version 10 was issued in April 1999. It updated the telescope offset and guider conversion diagrams to account for guiders which are in front of the rotator (like the NIRSPEC annular guider) and added an initial Keck II RNAS (NIRSPEC) picture.
- Version 11 was issued in May 1999. It updated the Keck II RNAS (NIRSPEC) picture after the first NIRSPEC commissioning run.
- Version 12 was issued in June 1999. It updated the Keck II RNAS (NIRSPEC) picture after the second NIRSPEC commissioning run.
- Version 13 was issued in July 1999. It updated the LWS pointing origin.
- Version 14 was also issued in July 1999. It updated the AO picture with the TSS (Tilt Sensor Stage) coordinate system and added an initial ESI picture.
- Version 15 was issued in September 1999. It updated the ESI picture with data obtained at the first commissioning run.

Appendix A Focal-station Pictures

This section contains a picture for each focal-station in regular use (not PCS for some reason).

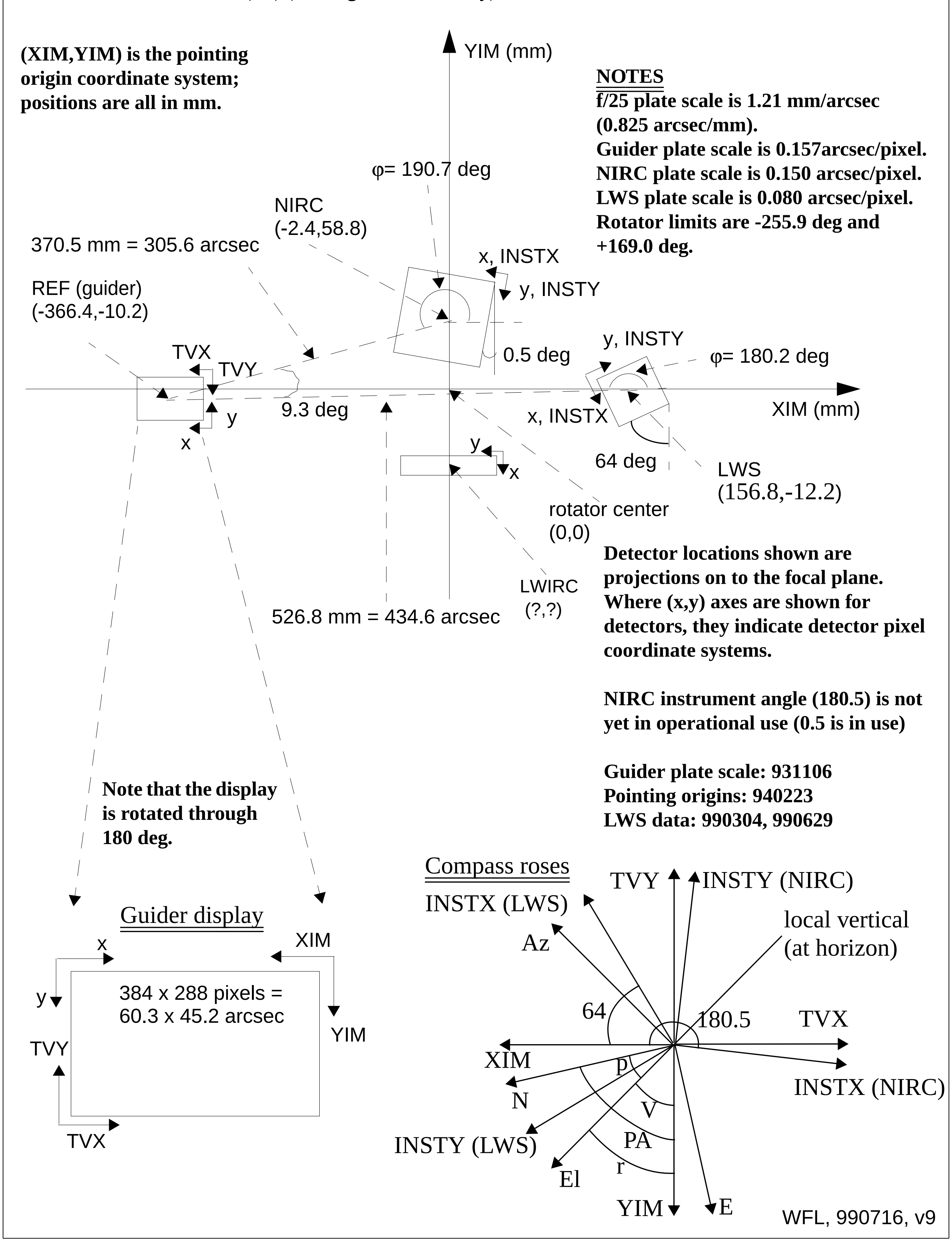
The main part of the picture shows the focal plane, the locations of the various detectors, their pixel coordinate systems, and the definitions (at the time of writing) of the various pointing origins.

The lower part of the picture gives details of the guider detector(s), including a version of Figure 3 specific to the focal-station and rotated so that it is easy to use when looking at the guider display. Note that the comments about arrow head directions and arrow signs on Figure 3, Figure 4 and Figure 5 apply to all of these pictures, namely that the figures are drawn so that all angles are positive and that arrow heads, where shown, serve only to indicate conventional direction of measurement, not sign.

Along the right-hand side of the picture are various notes on plate scales, rotator limits, dates at which measurements were taken etc.

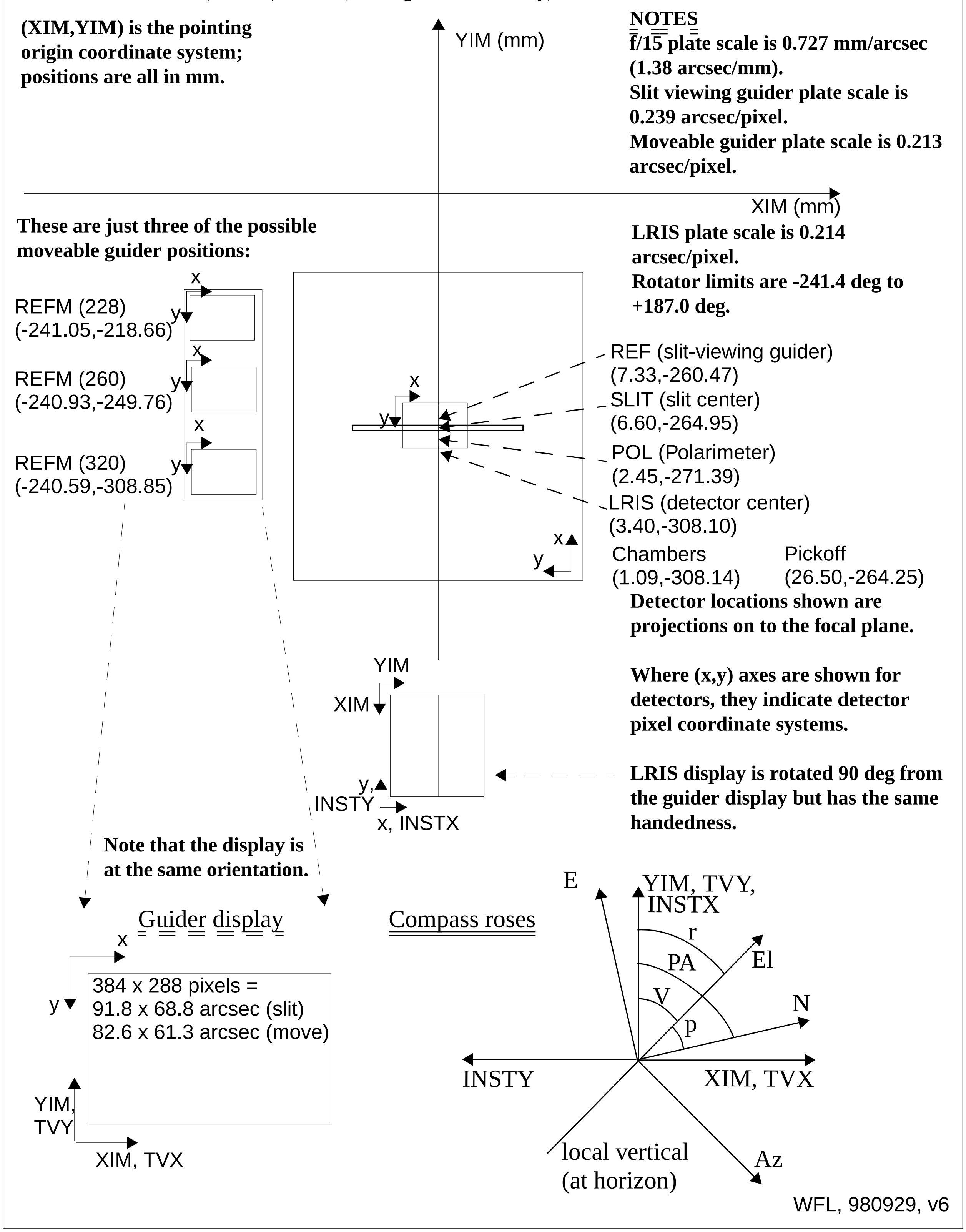
A.1 f/25 IR Frame (KI)

FIGURE 13. f/25 IR Frame (KI) (looking toward the sky)



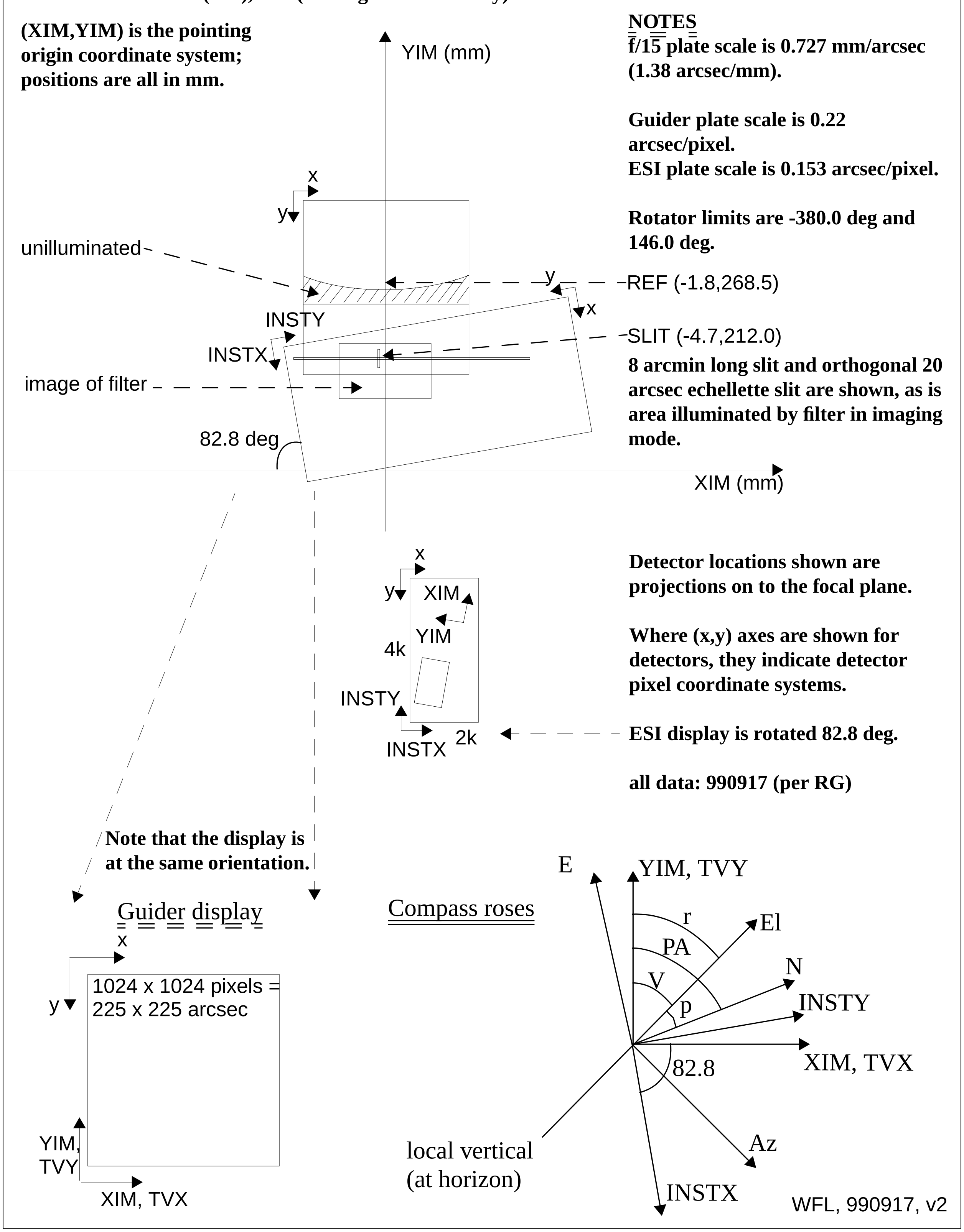
A.2 f/15 Cass (KI/KII), LRIS

FIGURE 14. f/15 Cass (KI/KII), LRIS (looking toward the sky)



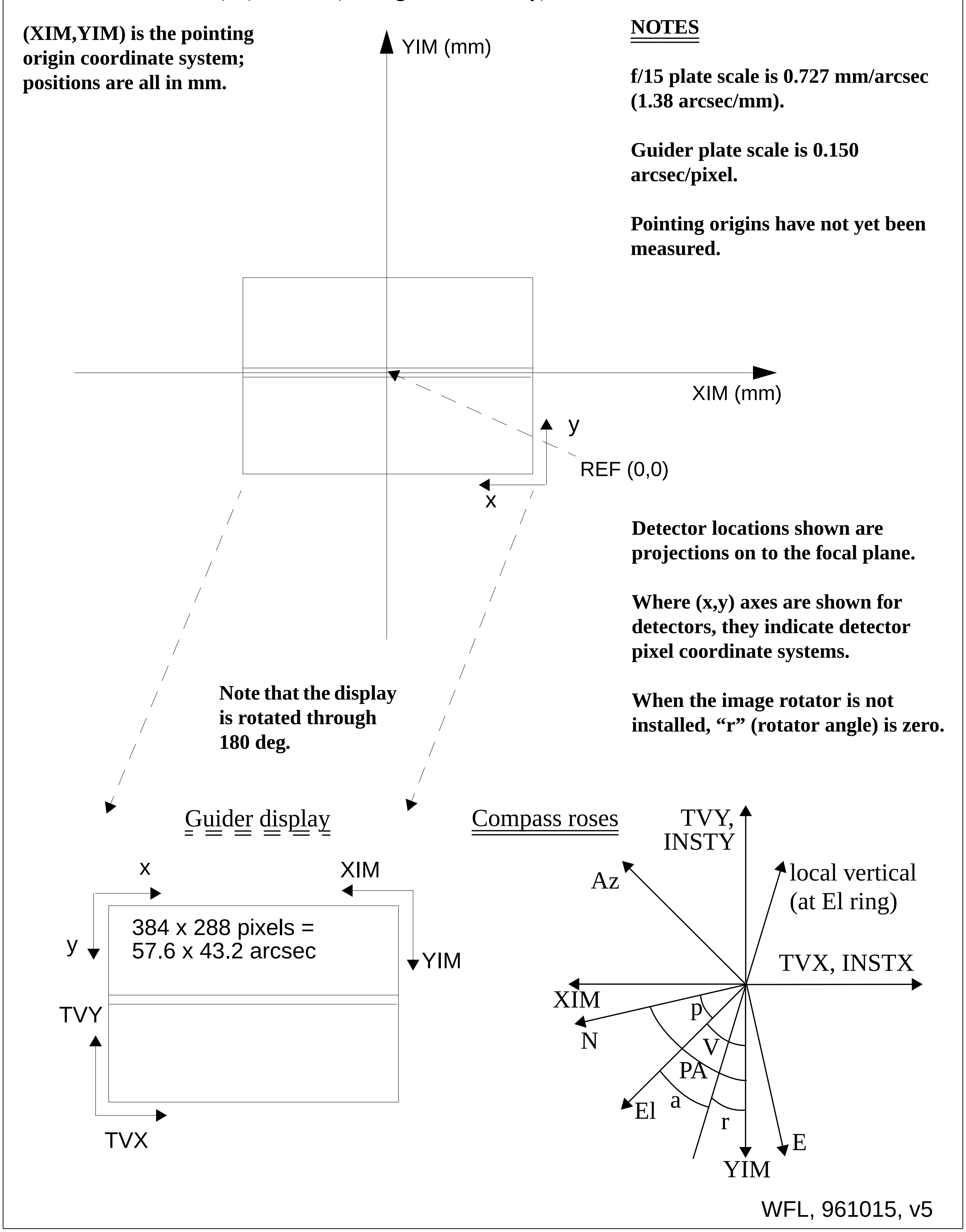
A.3 f/15 Cass (KII), ESI

FIGURE 15. f/15 Cass (KII), ESI (looking toward the sky)



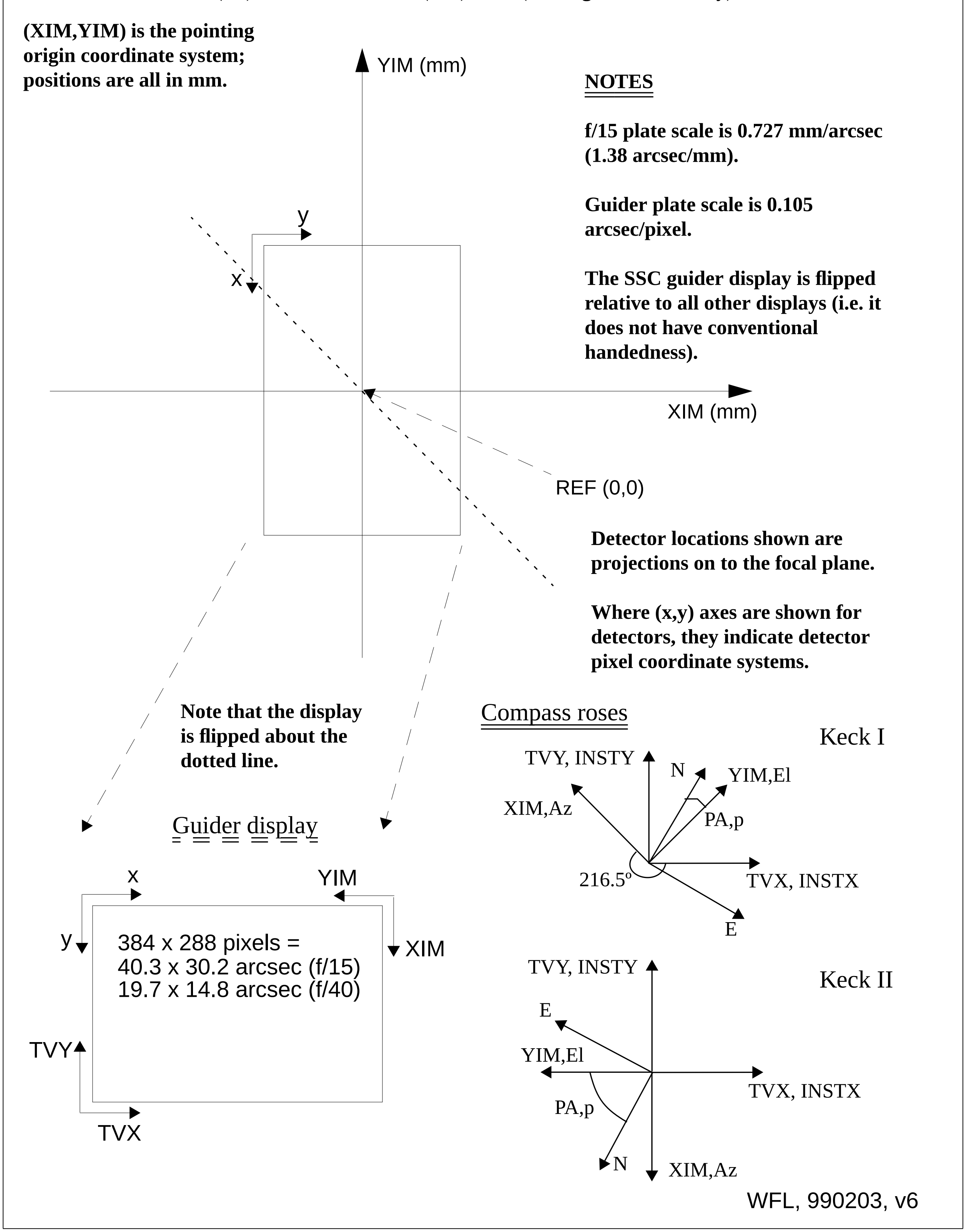
A.4 f/15 RNAS (KI), HIRES

FIGURE 16. f/15 RNAS (KI), HIRES (looking toward the sky)



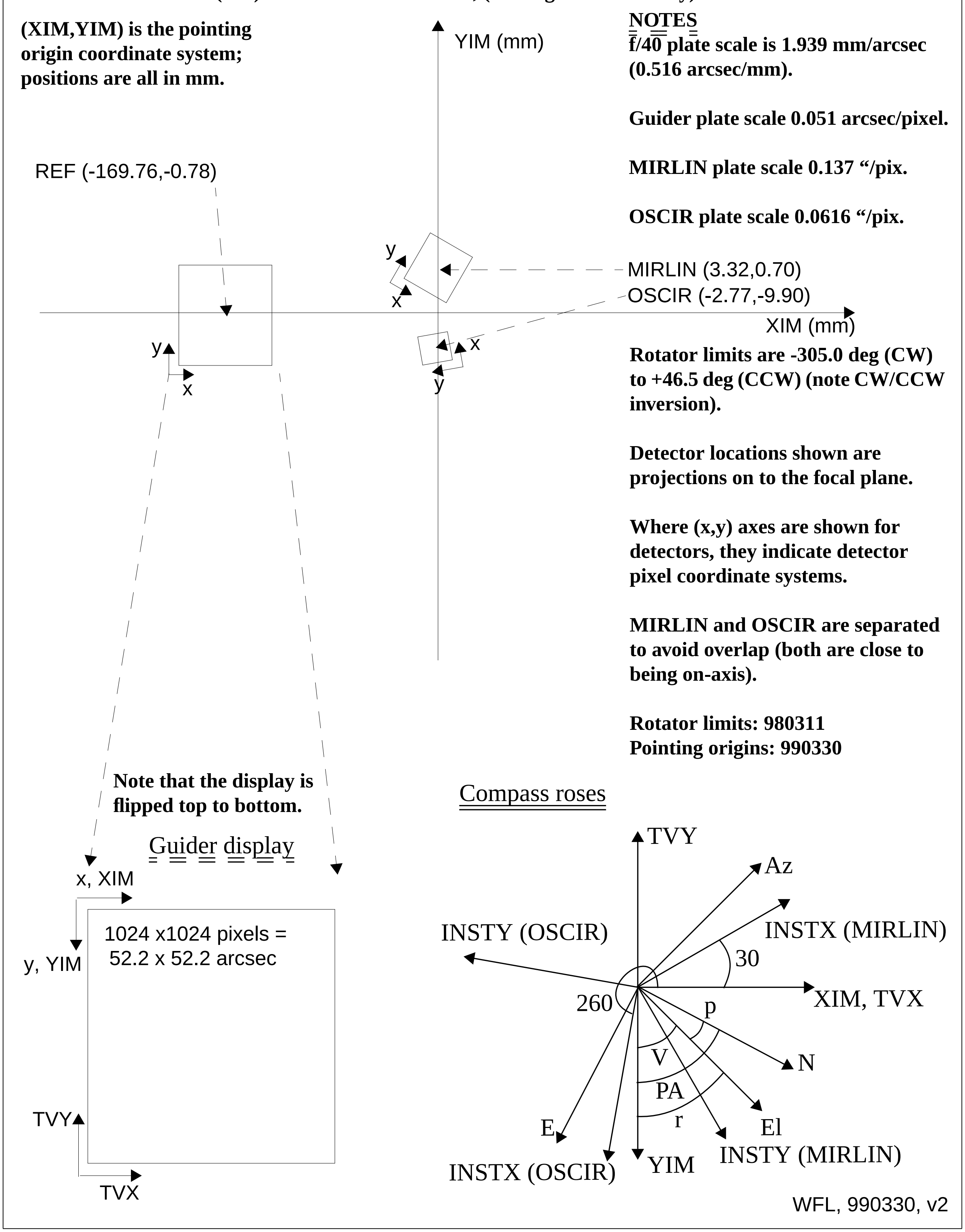
A.5 f/15 RBC2 (KI), f/15 or f/40 LBC2 (KII), SSC

FIGURE 17. f/15 RBC2 (KI), f/15 or f/40 LBC2 (KII), SSC (looking toward the sky)



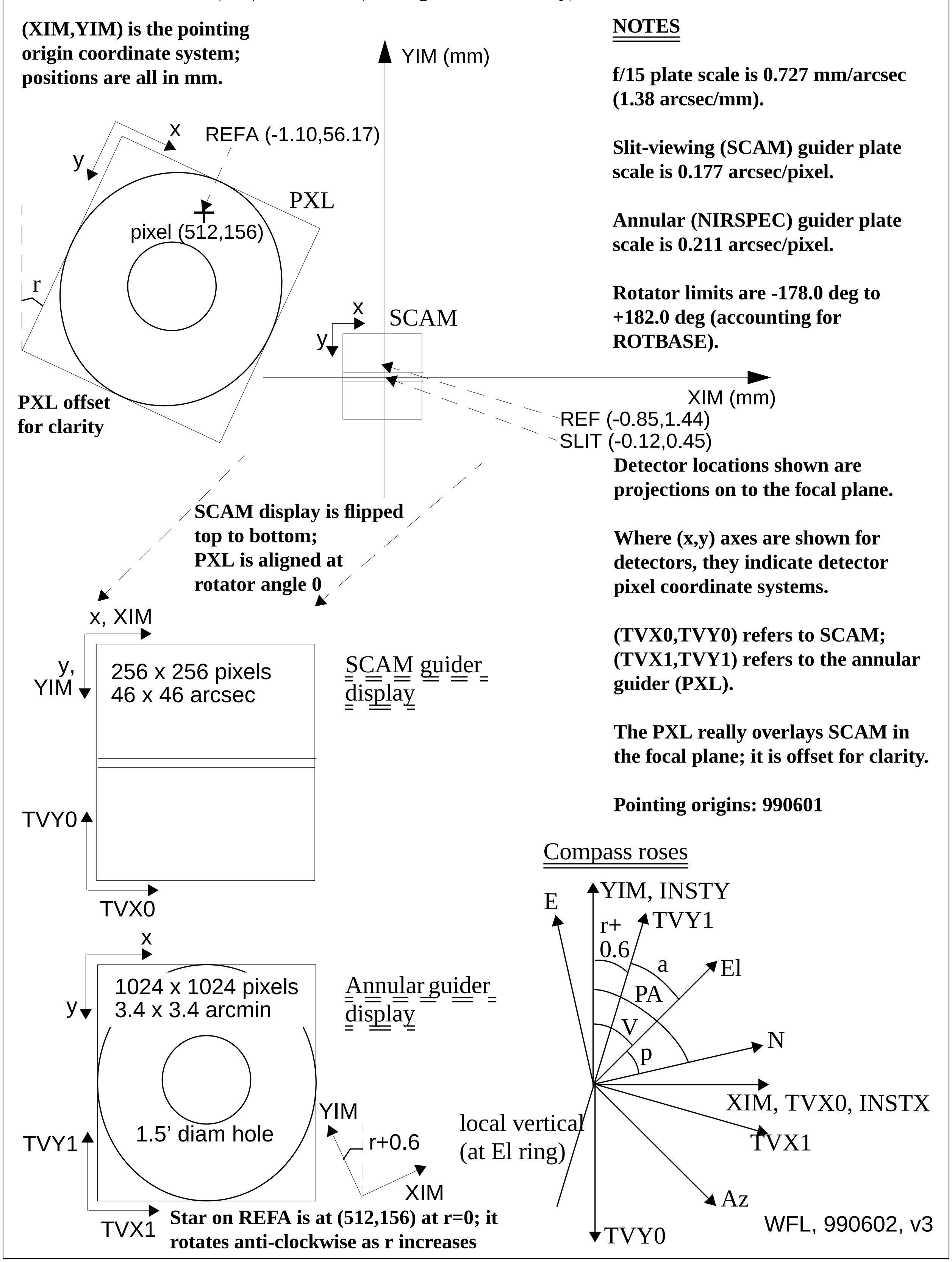
A.6 f/40 RBC2 (KII) Visitor Instrument Port

FIGURE 18. f/40 RBC2 (KII) Visitor Instrument Port, (looking toward the sky)



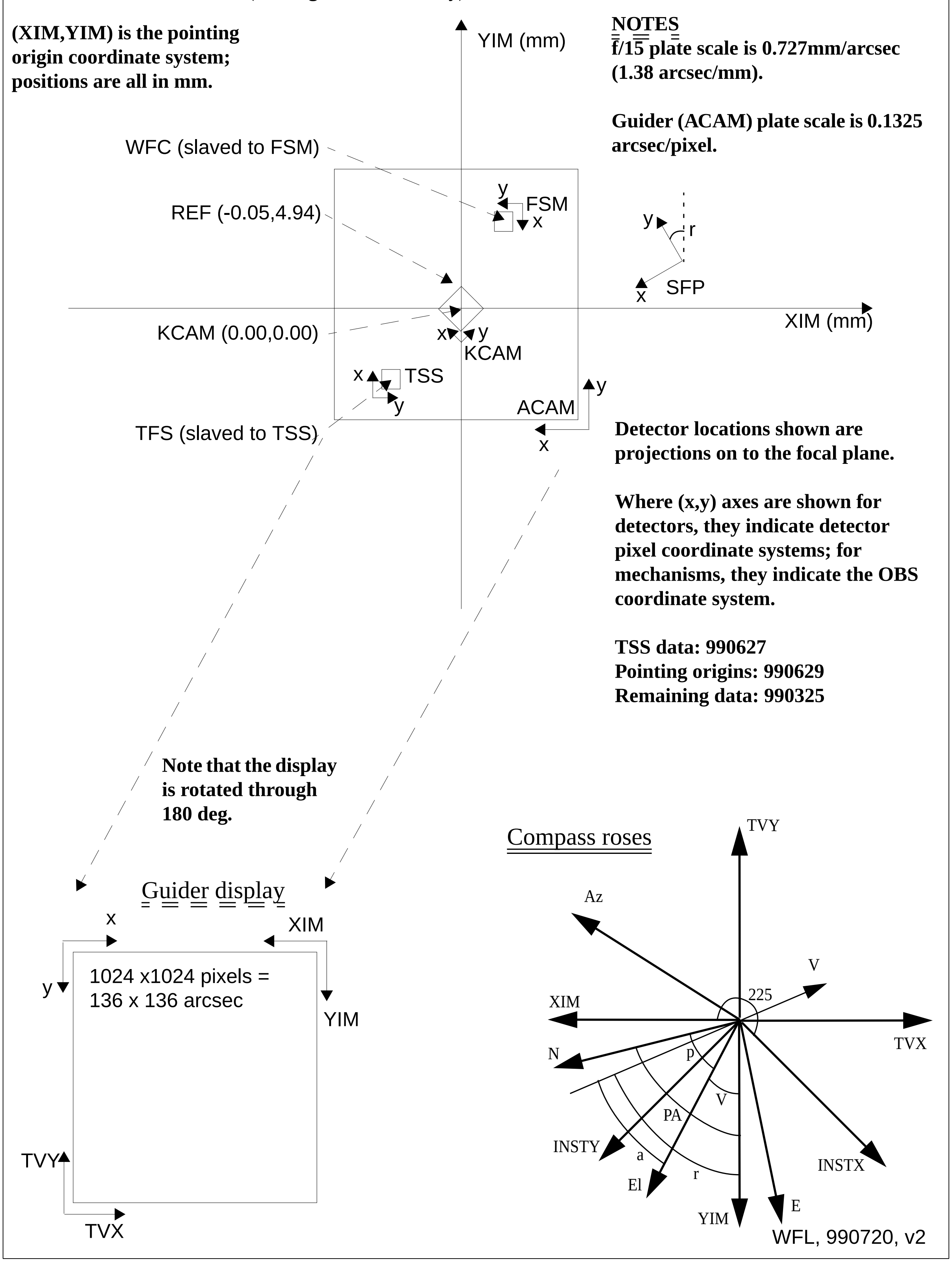
A.7 f/15 RNAS (KII) NIRSPEC

FIGURE 19. f/15 RNAS (KII) NIRSPEC (looking towards the sky)



A.8 f/15 LNAS AO

FIGURE 20. f/15 LNAS AO (looking towards the sky)



A.9 f/15 RNAS (KII) DEIMOS

FIGURE 21. f/15 RNAS (KII) DEIMOS (looking toward the sky)