HETDEX
Hobby-Eberly Telescope Dark Energy Experiment

McDONALD OBSERVATORY
THE UNIVERSITY OF TEXAS AT AUSTIN

Tracker Coordinates: A Proposal

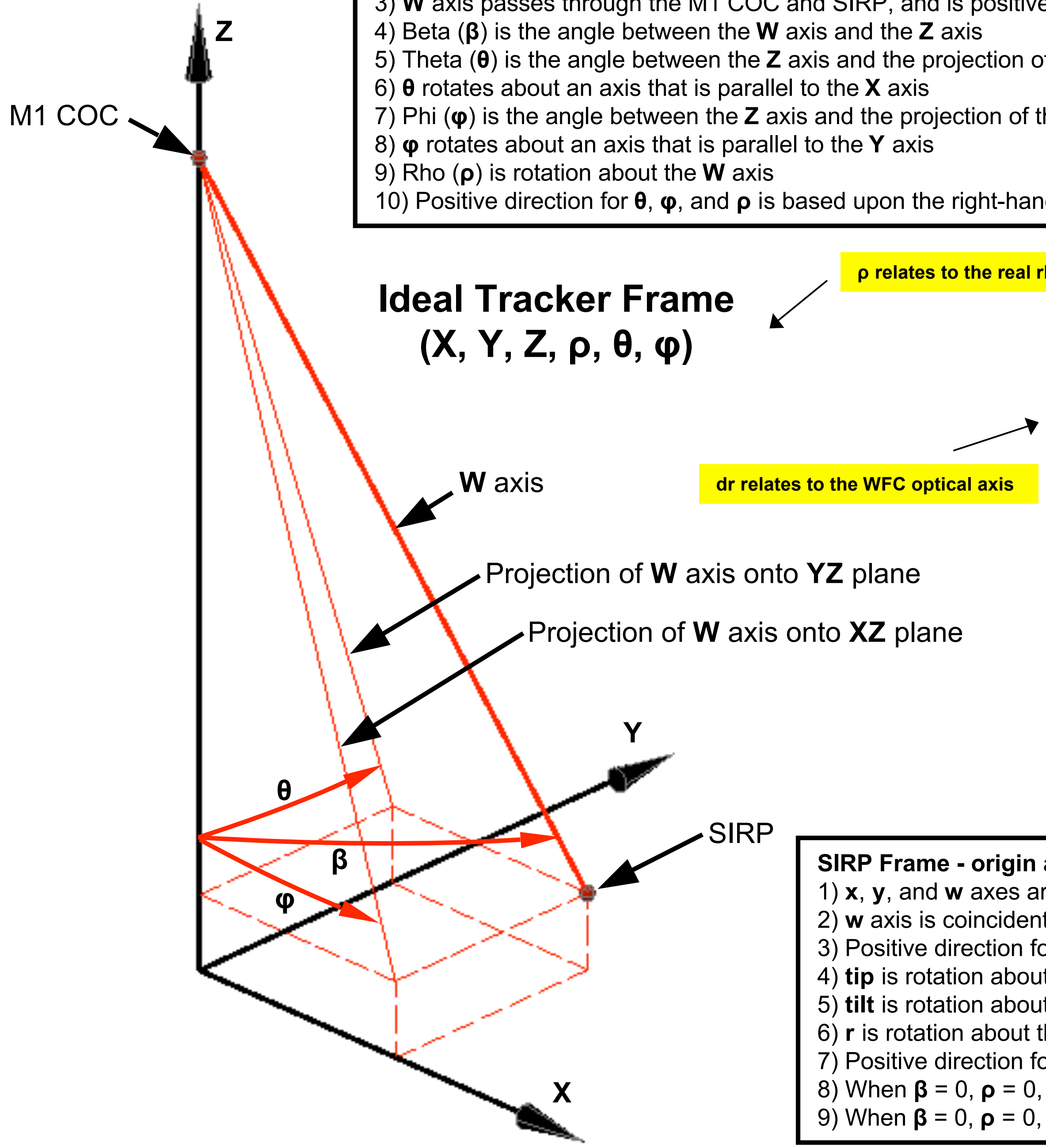
Trajectories in ITF, Corrections in SIRP frame

Version 0.2, 7/8/10

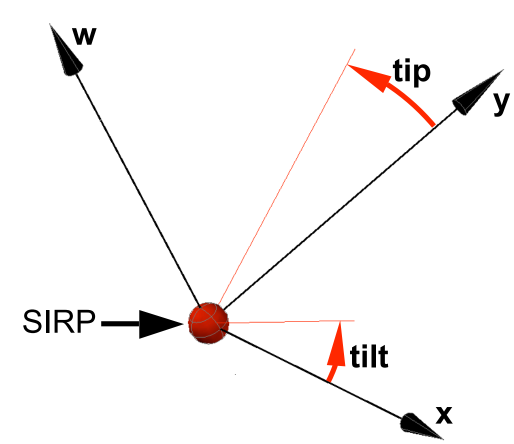
MEC

Ideal Tracker Frame (ITF) - origin on telescope optical axis, distance Fs from COC
1) **X**, **Y**, and **Z** axes are orthogonal
2) Positive direction for the **X**, **Y**, and **Z** axes is as shown by the arrows
3) **W** axis passes through the M1 COC and SIRP, and is positive towards the M1 COC
4) Beta (**β**) is the angle between the **W** axis and the **Z** axis
5) Theta (**θ**) is the angle between the **Z** axis and the projection of the **W** axis onto the **YZ** plane
6) **θ** rotates about an axis that is parallel to the **X** axis
7) Phi (**φ**) is the angle between the **Z** axis and the projection of the **W** axis onto the **XZ** plane
8) **φ** rotates about an axis that is parallel to the **Y** axis
9) Rho (**ρ**) is rotation about the **W** axis
10) Positive direction for **θ**, **φ**, and **ρ** is based upon the right-hand rule

Ideal Tracker Frame
(X, Y, Z, ρ, θ, φ)

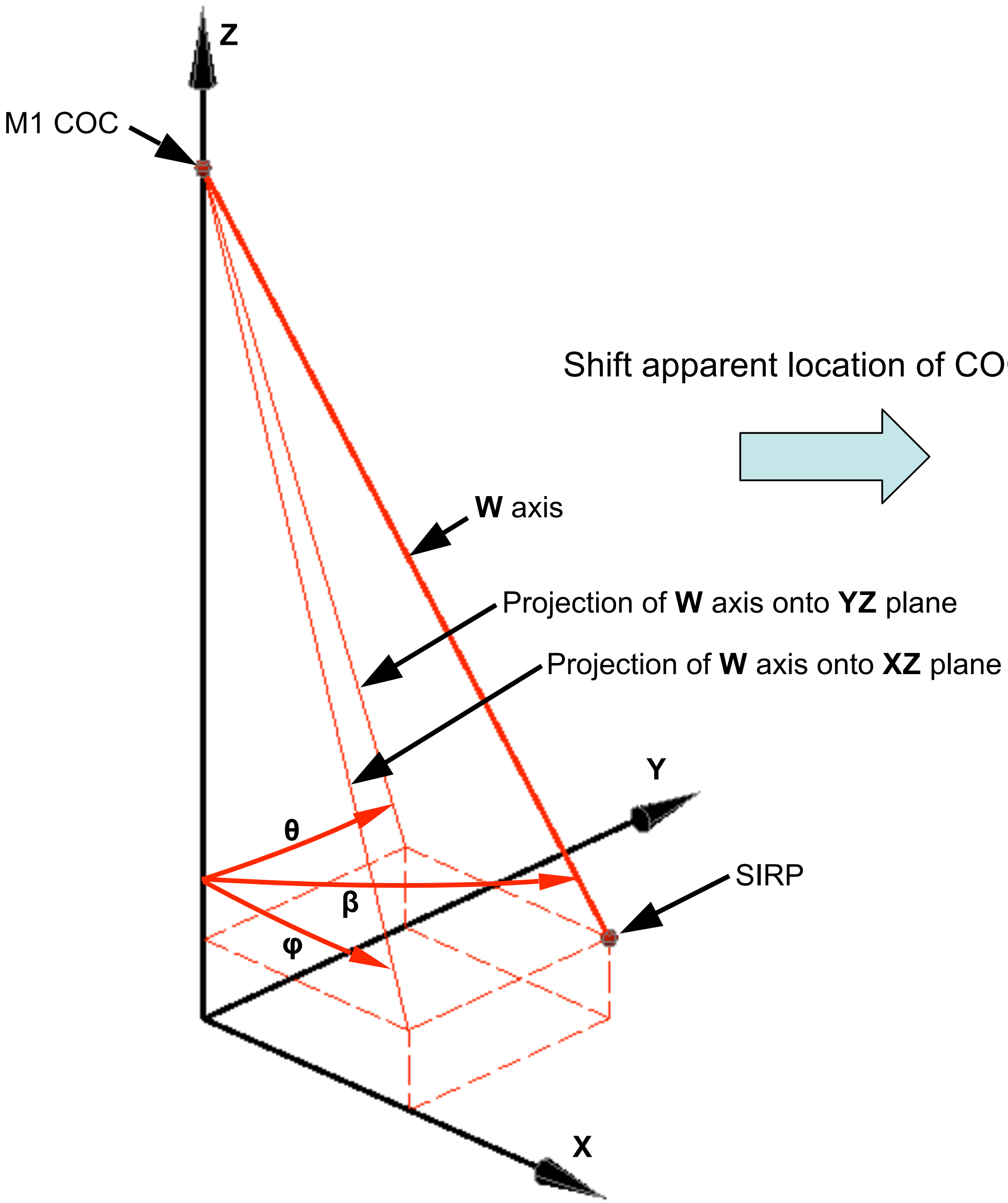


SIRP Frame
(dx, dy, dw, dr, tip, tilt)

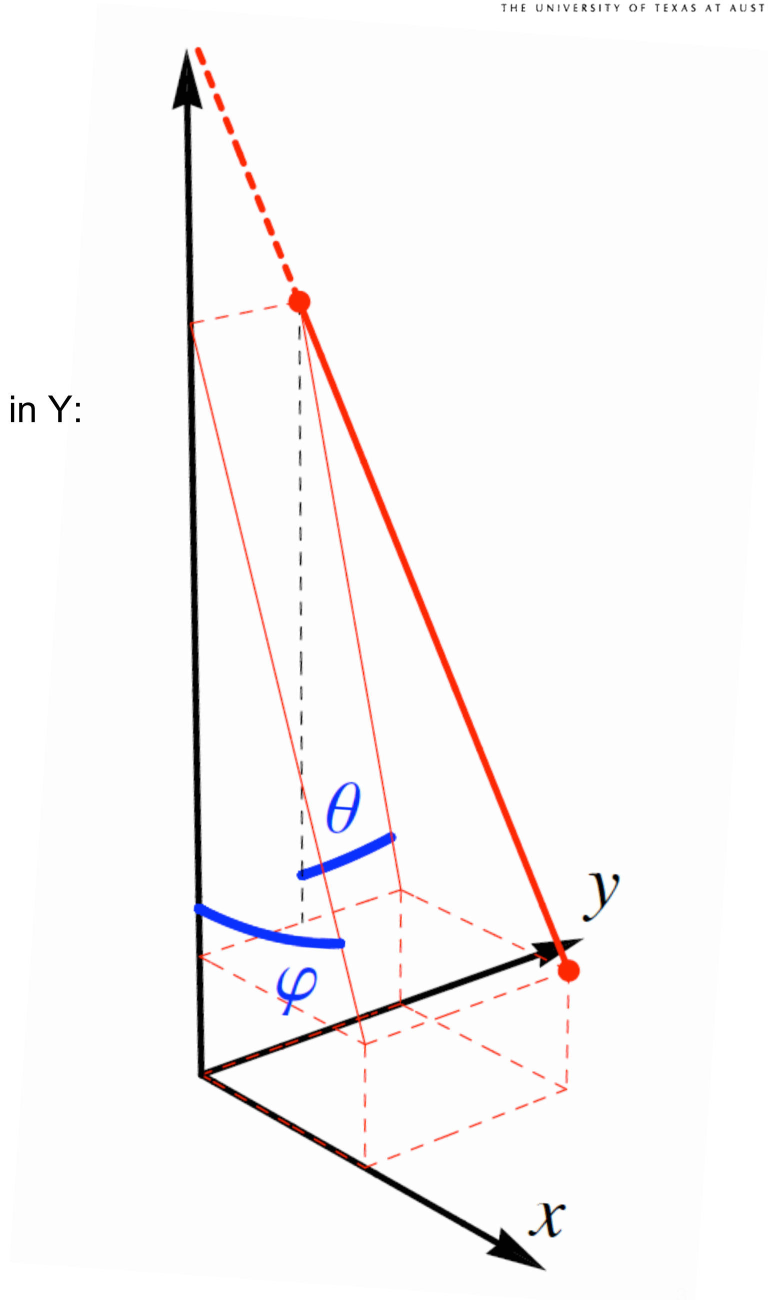


SIRP Frame - origin at SIRP
1) **x**, **y**, and **w** axes are orthogonal
2) **w** axis is coincident with the **WFC**'s optical axis
3) Positive direction for the **x**, **y**, and **w** axes is as shown by the arrows
4) **tip** is rotation about the **x** axis
5) **tilt** is rotation about the **y** axis
6) **r** is rotation about the **w** axis (not the same as **ρ** in ITF)
7) Positive direction for **tip**, **tilt**, and **r** is based upon the right-hand rule
8) When **β** = 0, **ρ** = 0, and **dr** = 0 the **x** and **X** axes are parallel to one another
9) When **β** = 0, **ρ** = 0, and **dr** = 0 the **y** and **Y** axes are parallel to one another

Arbitrary Orientation: Theta/Phi



Shift apparent location of COC in Y:



SIRP Frame Rotation Matrices

Assume signs on the angles from the right hand rule:

- Rx= [1 0 0
  0 cos(tip) -sin(tip)
  0 sin(tip) cos(tip)]

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(tip) & -\sin(tip) \\ 0 & \sin(tip) & \cos(tip) \end{bmatrix}$$

- Ry= [cos(tilt) 0 sin(tilt)
  0 1 0
  -sin(tilt) 0 cos(tilt)]

$$R_y = \begin{bmatrix} \cos(tilt) & 0 & \sin(tilt) \\ 0 & 1 & 0 \\ -\sin(tilt) & 0 & \cos(tilt) \end{bmatrix}$$

- Rz= [cos(dr) -sin(dr) 0
  sin(dr) cos(dr) 0
  0 0 1]

$$R_z = \begin{bmatrix} \cos(dr) & -\sin(dr) & 0 \\ \sin(dr) & \cos(dr) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Are these signs correct for right hand rule?

They don't match Hanshin's current code, but we should fix that to use a standard convention.

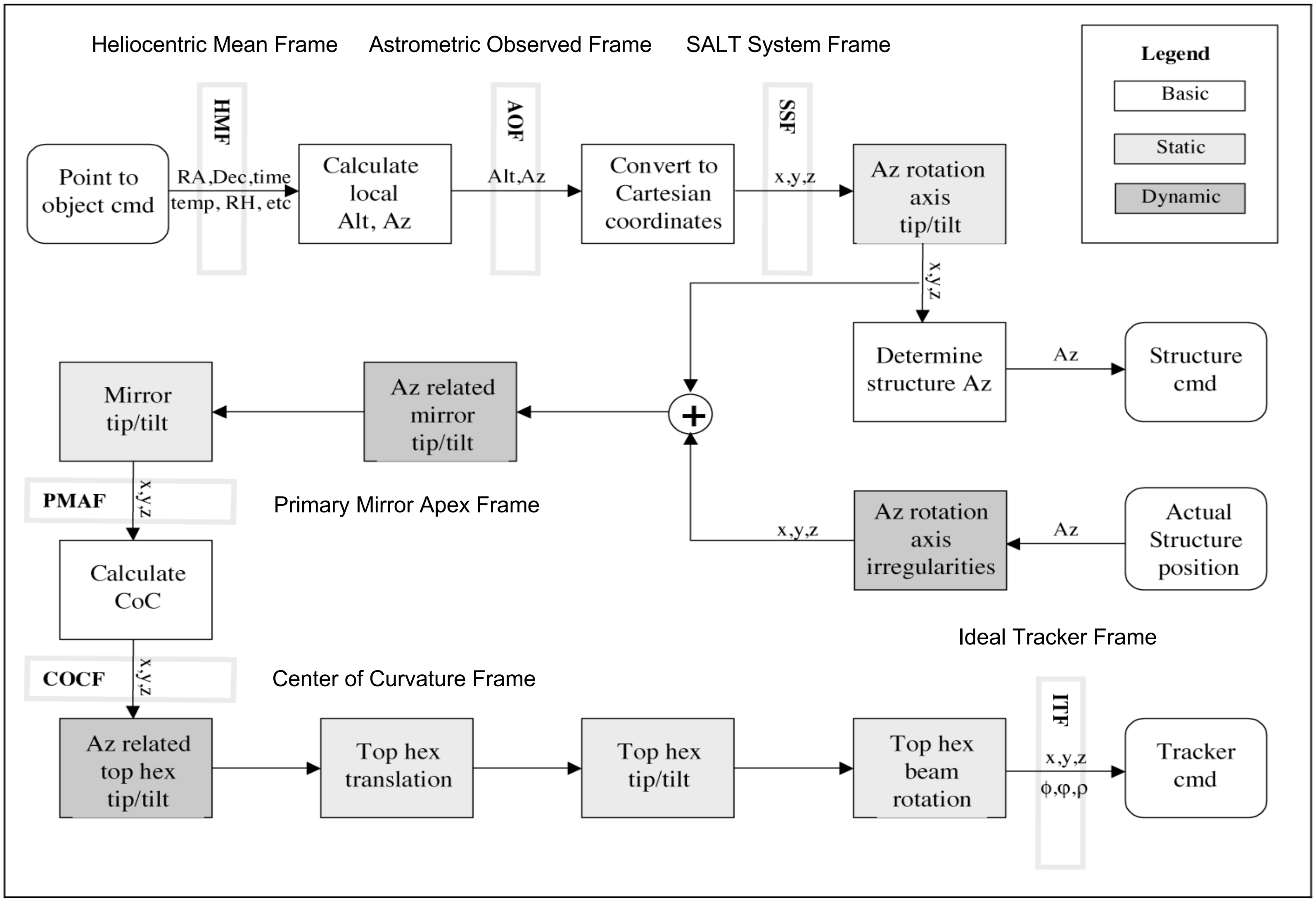
I'm confused about order:
Is this ITF -> SIRP or vice versa?
Or does it matter?

Finally, the order of application is Rx, Ry, Rz:

first rotate about the x axis through the angle "tip"
then rotate about the new y axis through the angle "tilt"
then rotate about the final z axis through the angle "dr"
finally apply required translation

SALT Mount Model

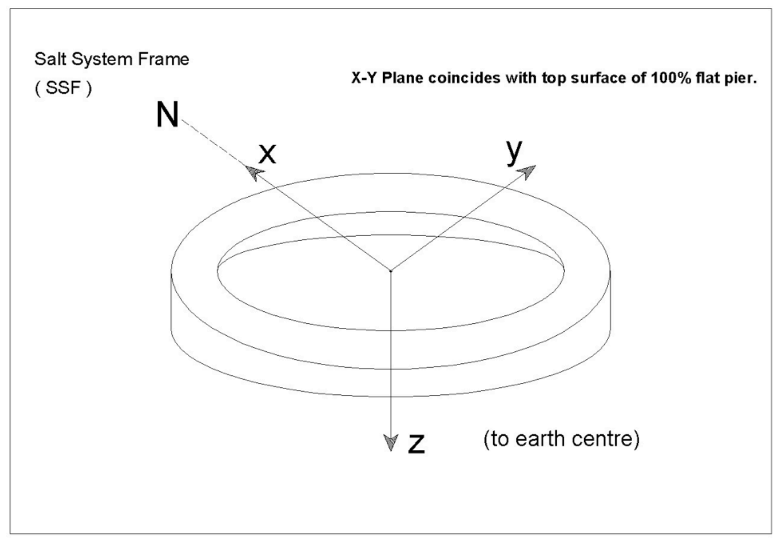
SALT Pointing Model Flow Chart:



SALT Reference Frames

SALT System Frame (SSF):

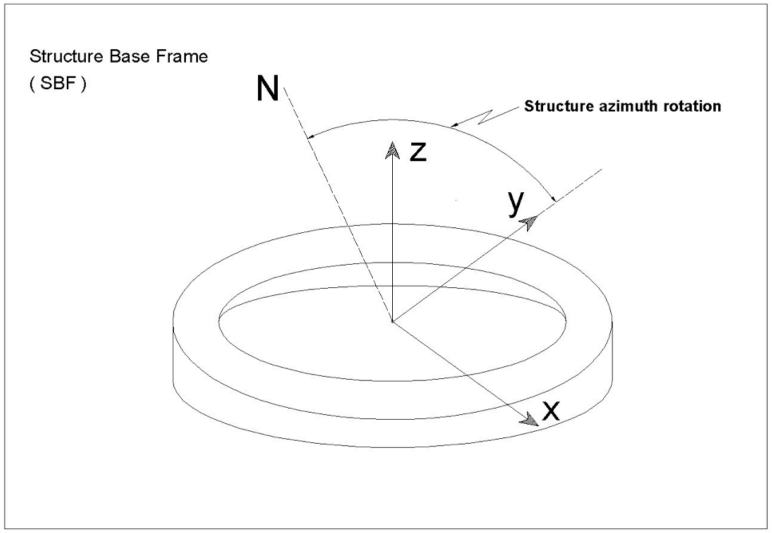
- Purpose: The position and attitude of all the SALT subsystems are defined relative to this frame.
- Origin: At center of pier, x-y plane coincident with top of 100% flat pier
- X-axis: Points north
- Y-axis: Completes right handed system (east)
- Z-axis: Points to center of earth



SALT Reference Frames (cont.)

Structure Base Frame (SBF):

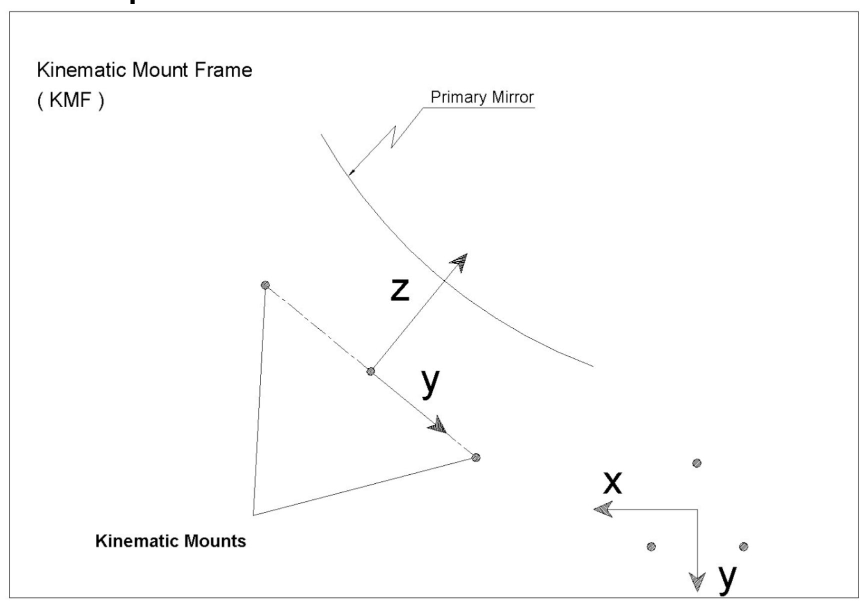
- Purpose: Used to define the position and attitude of the telescope structure.
  - The actual positions and displacements of the structure feet are given relative to this frame.
- Origin: Centered above the telescope pintle bearing, on level of pier
- X-axis: Points east when structure azimuth position is zero
- Y-axis: Points north when structure azimuth position is zero
- Z-axis: Up along axis of rotation



SALT Reference Frames (cont.)

Kinematic Mount Frame (KMF):

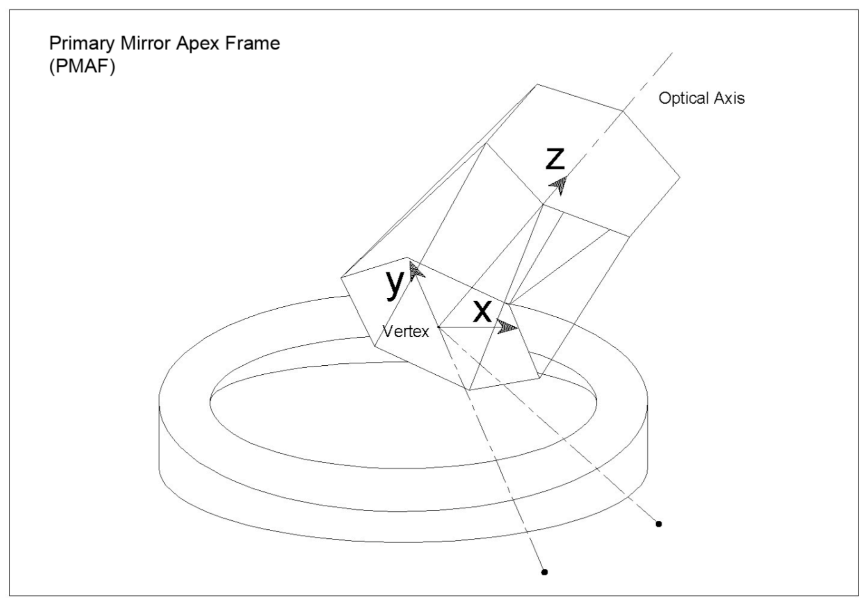
- Purpose: Positions of kinematic mounts must be relative to this frame.
  (All in x-y plane if the structure is perfect).
- Origin: Intersection of the optical axis and the plane of kinematic mounts, if the structure is perfect
- X-axis: Parallel to SBF x-axis, but in the opposite direction
- Y-axis: Points 37 degrees up from the horizontal, if structure is perfect
- Z-axis: Up along optical axis, if structure is perfect



SALT Reference Frames (cont.)

Primary Mirror Apex Frame (PMAF):

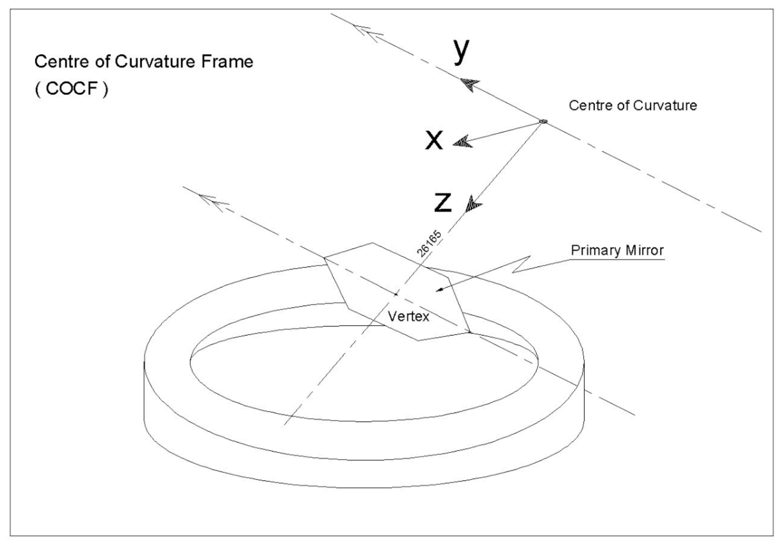
- Purpose: Used to define the position and attitude of primary mirror subsystems.
- Origin: At the vertex of the primary mirror
- X-axis: x-y plane tangential to vertex, x-axis completing the right handed system
- Y-axis: y-z plane coincident with telescope meridian when azimuth angle is zero, y pointing upwards
- Z-axis: Up from the vertex



SALT Reference Frames (cont.)

Center of Curvature Frame (COCF):

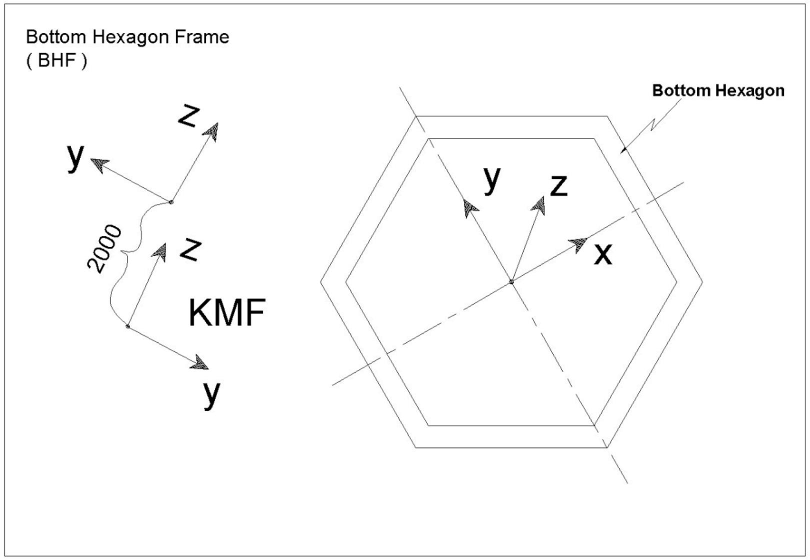
- Purpose: Used to define the position and attitude of the CCAS instrument and act as intermediary frame to calculate the tracker motions in ITF.
- Origin: At the center of curvature of the primary mirror
- X-axis: Parallel to ITF x-axis
- Y-axis: Parallel to ITF y-axis
- Z-axis: Perpendicular to the PMAF x-y plane pointing down towards the PM vertex



SALT Reference Frames (cont.)

Bottom Hexagon Frame (BHF):

- Purpose: Displacement of bottom hexagon relative to the structure base. This frame is used to model base wedge deformations.
- Origin: Center of bottom hexagon
- X-axis: Right handed complement
- Y-axis: Up (37 degrees) through the origin, if the structure is perfect
- Z-axis: Up along optical axis, if structure is perfect



SALT Reference Frames (cont.)

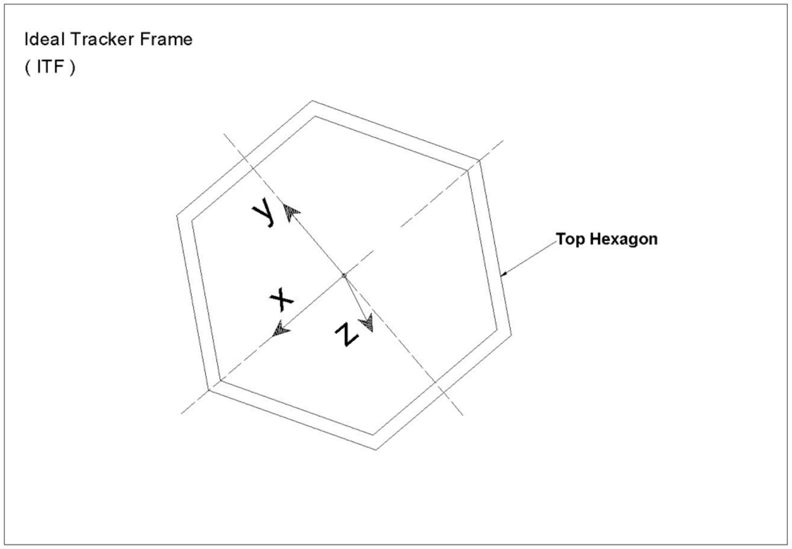
Top Hexagon Frame (THF):

- Purpose: Used as an intermediary frame to calculate ITF. This frame is fixed to the top hex beams on which the tracker runs.
- Origin: At the intersection of the optical axis and the plane formed by the top hex beams. (The x-y plane coincides with the idealized beam plane.)
- X-axis: Right handed complement
- Y-axis: Up (37 degrees) through origin, if structure is perfect
- Z-axis: Up along optical axis, if structure is perfect

SALT Reference Frames (cont.)

Ideal Tracker Frame (ITF):

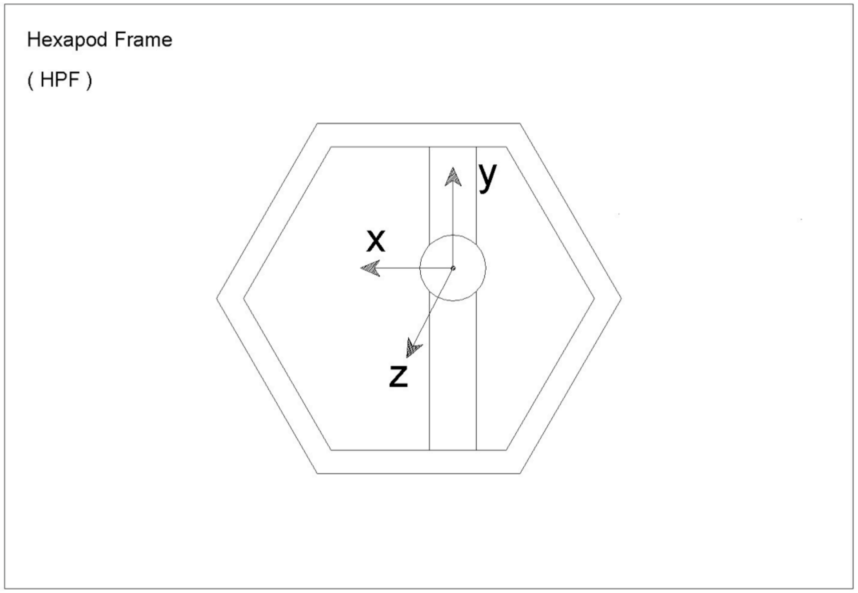
- Purpose: All the tracker motions are defined relative to this frame.
  Any deviations from the ideal tracker beam should be compensated for by making adjustments to these commands.
- Origin: At the vertex of the PM, x-y plane coincident with ideal x-bearings
- X-axis: In x-drive direction
- Y-axis: Positive in y-drive direction (uphill)
- Z-axis: Pointing to the PM vertex
  Note that HET uses opposite sign.



SALT Reference Frames (cont.)

Hexapod Frame (HTF):

- Purpose: Used as intermediary frame to calculate Hexapod strut lengths, this frame is fixed to the payload and its attitude relative to the ITF frame is given by ϕ about x_0, θ about y_1, ρ about z_2, in order of rotation from ITF to HPF.
- Origin: At rotation point of Payload
- X-axis: Parallel to ITF x-axis
- Y-axis: Parallel to ITF y-axis
- Z-axis: Parallel to ITF z-axis

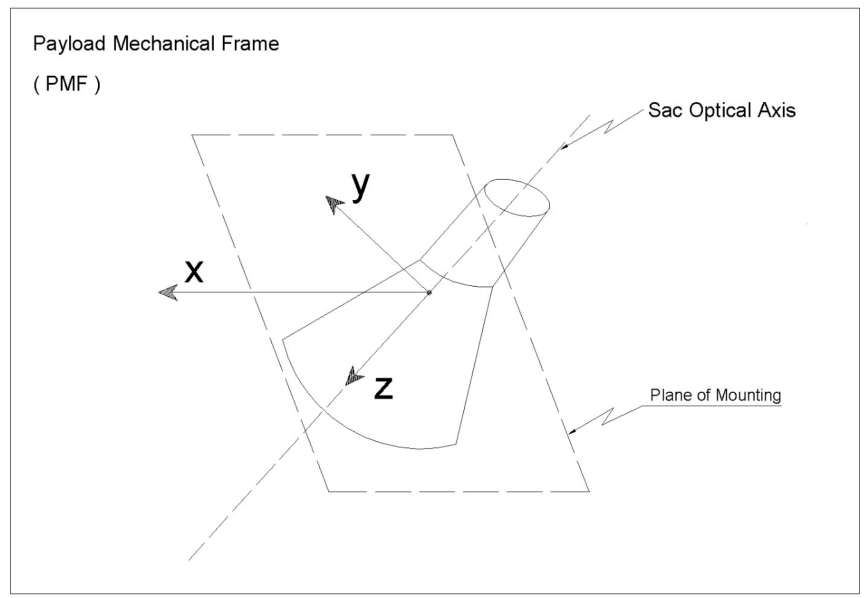


SALT Reference Frames (cont.)

Payload Mechanical Frame (PMF):

- Purpose: To define position and attitude of payload subsystems.
- Origin: At center of payload structure in the plane of mounting on the rotation stage with the x-y plane parallel to the ITF x-y plane at PM vertex
- X-axis: Coincident with ITF x-axis in zero position
- Y-axis: Coincident with ITF y-axis in zero position
- Z-axis: Pointing down along SAC optical axis

  Note that HET uses opposite sign.



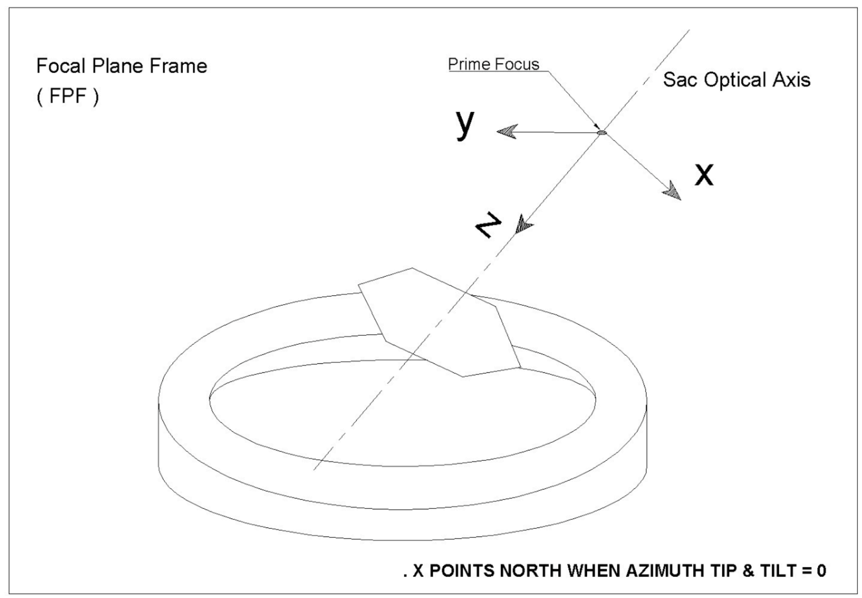
SALT Reference Frames (cont.)

Focal Plane Frame (Prime Focus) (FPF):

- Purpose: To define image positions at prime focus.
- Origin: At the center of prime focus.

  The x-y plane coincides with the image plane.
- X-axis: X pointing north when azimuth and payload tip and tilt angles are zero
- Y-axis: y-z plane coincident with telescope meridian when azimuth and payload tip and tilt angles are zero, Y completes the right handed system
- Z-axis: Down along SAC optical axis

  Note that HET uses opposite sign.



General Notes

Now coordinates and corrections will be in different coordinate systems:

- Trajectories, plus relative and absolute moves, are described in ITF
  - ITF is the natural system for computing a trajectory
- Corrections are described AND applied relative to the SIRP
  - Our metrology produces measurements naturally in this frame
  - Tip/Tilt must be applied as rotations about SIRP to avoid scan on sky
- Both ITF and SIRP coordinate systems are defined by the optics
  - ITF relative to the optical axis of primary mirror, at radius Fs from COC
  - SIRP is a point along the optical axis of the Wide Field Corrector
- => Transformations are required to relate to physical hardware
  - ITF coords relative to the upper hex or points on upper, lower X rails
  - SIRP coords relative to the strongback, or elsewhere on hexapod frame
- For ITF, X=Y=0 on PM optical axis, Z=0 at radius Fs from COC
- For SIRP, coordinates are 0 when WFC is pointing at COC
  - Goal of metrology system is to drive these to zero

Meaning of θ, φ in ITF

- For "can-on-a-string", these are defined in HET Tech. Report #42
  - p. 7, equations (16) and (17)
- Can also be used to specify an arbitrary orientation for the WFC
  - θ, φ are used to define two direction cosines used to orient hexapod
    - See the C code from current control system in Calc_Hex_Pos.c
    - See Jim Fowler's documentation for that code in FullWriteUp.pdf
      - "Hexpods at the Hobby Eberly Telescope"
  - This arbitrary orientation amounts to pointing the WFC at a new COC
  - This formulation reduces to the figure on Slide 2 for "can-on-a-string"
- θ is negative for negative Y values
- φ is negative for negative X values
  - See the example trajectory plot and table (for the current tracker)
    - ITF: trajectory+60.pdf, trajectory+60.dat
    - Hexapod leg lengths: hexapod+60.pdf, hexapod+60.dat

- Possible red herring:
  - φ is defined via a left hand rule inside the current tracker

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HET Technical Report #42

HET HOBBY ★ EBERLY TELESCOPE

HET Technical Report #42

Tracker Mechanism Kinematics, Servo, and Top-level Software Design for a Semi-transit Telescope with Fixed Spherical Primary Mirror

F. B. Ray

Hobby ★ Eberly Telescope Project
McDonald Observatory
University of Texas
RLM 15.308
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April 4, 1994

A Joint Project of
The University of Texas at Austin, The Pennsylvania State University,
Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen

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Definition of Theta and Phi

about the center of curvature of the primary mirror. Prime focus spectrometer apertures also require correction for field rotation as a rotation point is tracked across the available gantry space, and the optical corrector near prime focus benefits from 2-axis tip/tilt freedom about an optical node for coma correction and fine guiding (the "coma-neutral" node). We therefore must project the space curve marked "**RP** trajectory" in figure 4 to a Cartesian coordinate system related to the gantry mechanism and the tilt mechanisms it carries.

Relating the above spherical tracking triangles to a Cartesian coordinate system fixed to the telescope's upper surface, we require several auxiliary variables. First, we define 2D rectangular coordinates (**r**,**d**) for a system whose **R** axis is perpendicular to the transit plane, as

$$\mathbf{r}(t) = \mathbf{F_S} \cos \delta(t) \sin \mathbf{h_c}(t) \quad (10)$$

$$\mathbf{d}(t) = \mathbf{F_S} [\sin (\delta_\mathbf{T} - \delta_\mathbf{c}) + \sin \delta_\mathbf{c} (\cos \delta_\mathbf{T} - \cos \delta(t) \cos \mathbf{h_c}(t))] \quad (11)$$

which is of the form

$$\mathbf{d}(t) = \mathbf{F_S} [C5 - C2 \cos \delta(t) \cos \mathbf{h_c}(t)] \quad (12)$$

if

$$C1 = \sin (\delta_\mathbf{T} - \delta_\mathbf{c}),\ C2 = \sin \delta_\mathbf{c},\ C3 = \cos \delta_\mathbf{T},\ C4 = C2\ C3, \text{ and } C5 = C1 + C4 \quad (13)$$

and $\mathbf{F_S}$ is the radius of the tracking sphere.

Then, with a parallactic rotation $\mathbf{p_c}$ about the telecentric axis, we obtain **x** and **y**, coordinates in a hypothetical mechanism's X and Y (mechanical) directions,

$$\mathbf{x}(t) = \mathbf{r}(t) \cos \mathbf{p_c} - \mathbf{d}(t) \sin \mathbf{p_c} \quad (14)$$

$$\mathbf{y}(t) = \mathbf{r}(t) \sin \mathbf{p_c} + \mathbf{d}(t) \cos \mathbf{p_c} \quad (15)$$

Projection angles θ(t) and φ(t) related to the tracker's Cartesian coordinate system are then

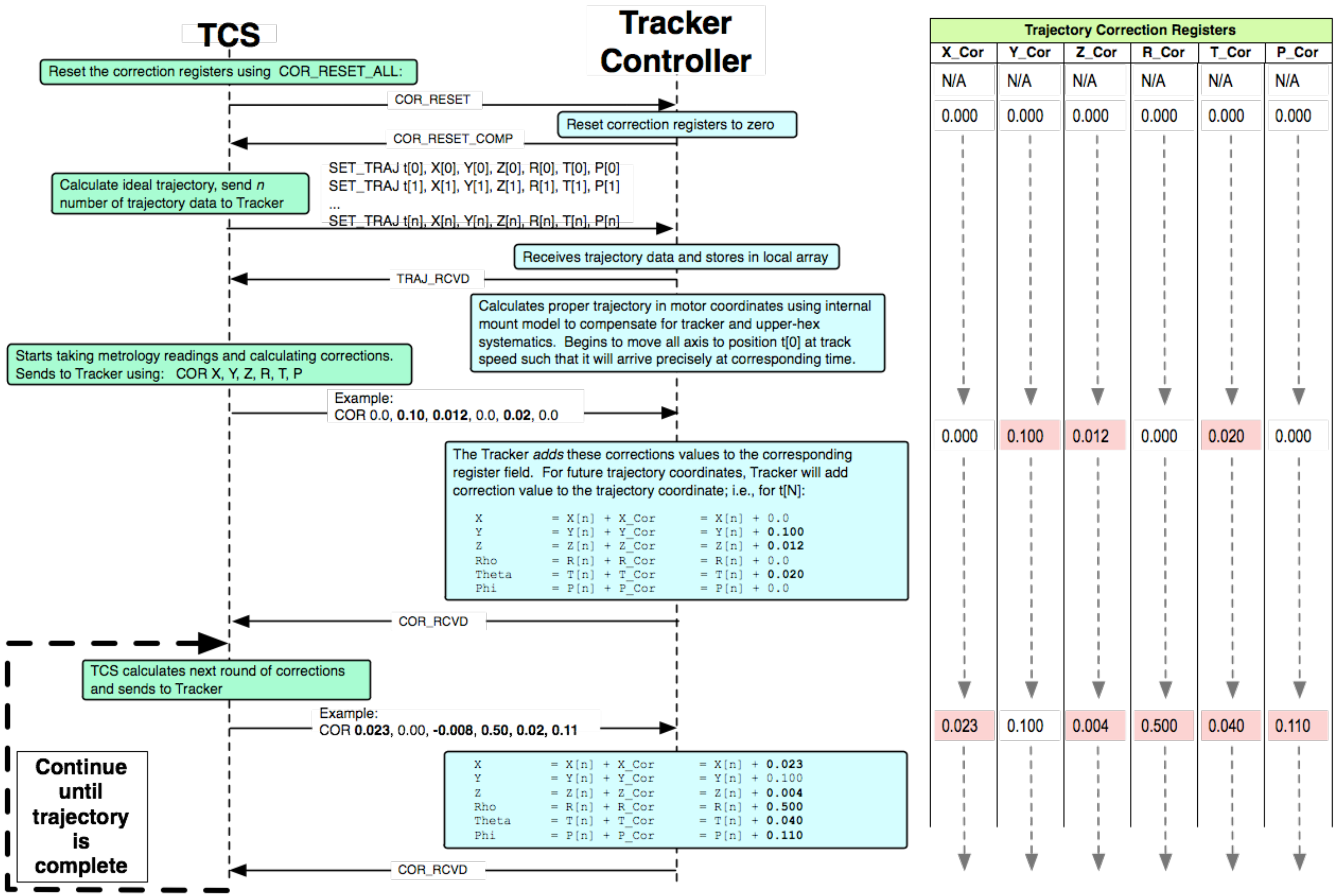
$$\theta(t) = \tan^{-1}\left[\frac{\mathbf{y}(t)}{\mathbf{F_S} \cos \beta(t)}\right] \quad (16)$$

$$\phi(t) = \tan^{-1}\left[\frac{\mathbf{x}(t)}{\mathbf{F_S} \cos \beta(t)}\right] \quad (17)$$

The displacement parallel to the telecentric axis we define as **z**(t) (also called the tracking sagitta), given by

$$\mathbf{z}(t) = \mathbf{F_S} [1 - \cos \beta(t)] = \mathbf{F_S} - \sqrt{\mathbf{F_S}^2 - \mathbf{x}(t)^2 - \mathbf{y}(t)^2} \quad (18)$$

Needs tweaking:
Trajectory Correction Strategy



Correction Scheme

- The correction scheme that we have discussed previously needs tweaking:
  - We now intend to send corrections in the SIRP frame
  - These corrections are no longer simple offsets to *ITF* coordinates
  - Corrections in the SIRP frame will need to be transformed to offsets that can be added to the internal coordinates the tracker is using to follow a trajectory

- And we can’t forget:
  - We need to be able to transform the current tracker position back to ITF
    - Describing its actual position and orientation
    - Using a forward transformation scheme as described in Jim’s writeup
    - Note that forward transform works fine, to high accuracy, for current tracker

- And no, I can’t write down all of the required transformations

Tracker API

MOVR_TCS [X, Y, Z, ρ, θ, φ] [speed = SLEW|TRACK|vel]

Initiates a relative (incremental) move in ideal tracker frame coordinates at either slew speed, track speed, or else at the velocity specified.

MOVA_TCS [X, Y, Z, ρ, θ, φ] [speed = SLEW|TRACK|vel]

Initiates an absolute move in ideal tracker frame coordinates at either slew speed, track speed, or else at the velocity specified.

MOVR_TRK [X,Y,ρ,H_1,H_2,H_3,H_4,H_5,H_6] [SLEW|TRACK|vel]

Initiates a relative (incremental) move in tracker coordinates at either slew speed, track speed, or else at the velocity specified.

MOVA_TRK [X,Y,ρ,H_1,H_2,H_3,H_4,H_5,H_6] [SLEW|TRACK|vel]

Initiates an absolute move in tracker coordinates at either slew speed, track speed, or else at the velocity specified.

SLEW and TRACK boil down to fast and slow;
'vel' allows us to specify a speed if moving one axis