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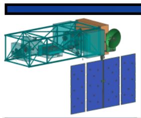

SIM (Lite)

SIM Data Analysis [How to create calibrated regularized delays]

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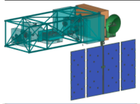
24-September-2008

Recap: SIM Overview



SIM (Lite)

- SIM observes of several different types of science objects:
  - G = Grid stars - used to form astrometric grid and instrument ‘self-calibration’
  - Q = Quasars - used to correct grid zonal errors
  - W = Wide-angle (WA) targets
  - N = Narrow-angle (NA) targets
  - R = Reference stars (used in association with N to improve astrometric accuracy)
- SIM observing consists of 3 phases:
  1. Create schedule containing G,Q,W,N,R science observations to undertake
  2. Execute schedule using SIM-Lite spacecraft
     - Create a set of regularized delays d_{reg} for G,Q,W,N,R observations
  3. Data analysis of regularized delays
     1. Convert d_{reg} into a form that can be used by astronomers (d_{cal})
     2. Astronomers analyze subset of d_{cal} data for own astronomical projects

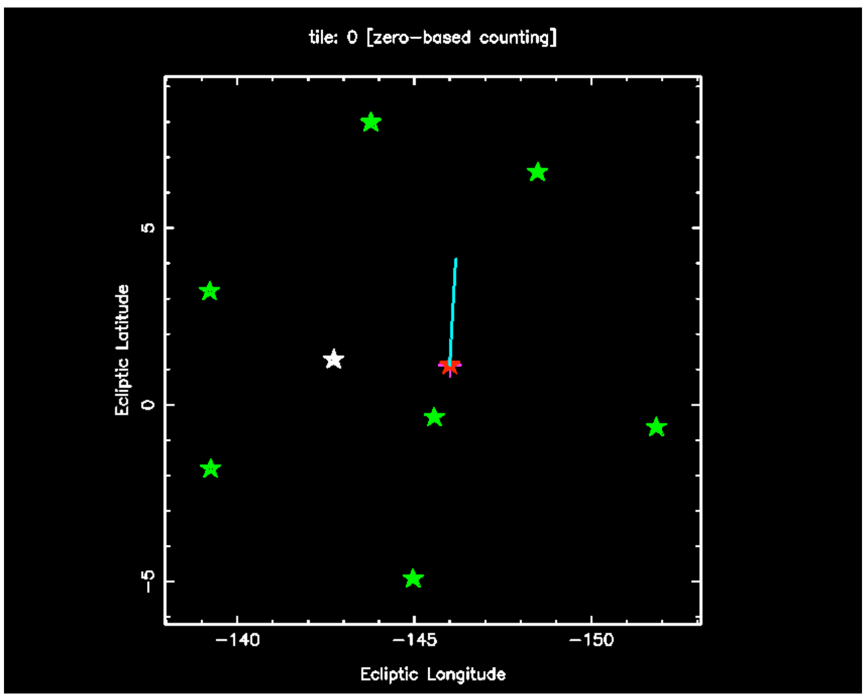
•Mission science output = f(schedule, SIM-Lite instrument properties, project data analysis, astronomers data analysis)

•Our insight into entire process is gained by use of SIM-sim (End-to-End simulator of the SIM mission)

Recap: How does SIM observe?

SIM (Lite)

- SIM observes in tiles [which have 15° diameter]
- Each tile lasts ~1 hr and there are ~45,000 tiles in a 5-yr mission
- ~1300 Grid stars must be observed so that spacecraft calibration parameters can be determined:
  - single-tile: constant term and 2 baseline orientations
  - multi-tile: baseline-length and field-dependent errors (FDEs)

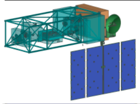


Example tile:

- G-stars in green
- W-target in white
- Guide1 star in red [at center of field]
- Baseline orientation in cyan

Note: must have at a least 3 grid stars observed per tile with one observed twice so that linear drift effects can be Removed. Typically have 6-7 Grid stars in a tile

What is a regularized delay (d_{reg})?



SIM (Lite)

- Instantaneous raw delay: $d_{raw}(t)$
  - SIM measures delay every *science readout time* (e.g., every ~0.1s) on an instantaneous baseline

    $$d_{raw}(t) = d_{delay\_line}(t) + \eta_{white\_light}(t)$$
  - The baseline orientation is affected by attitude drift and control
  - Because the science baseline is not fixed in space, delays measured on it cannot be immediately and coherently averaged
- Instantaneous regularized delay: $d_{reg}(t)$
  - Each raw delay is "regularized" (corrected) to be that which would have been measured on a fiducial ("regularized") baseline $\mathbf{b}_{reg}$ that remains *fixed in space for a tile:*

    $$d_{reg}(t) = d_{raw}(t) + [\mathbf{b}_{reg} - \mathbf{b}_{est}(t)] \cdot \mathbf{s}$$

    where
    - $\mathbf{b}_{est}$ = best estimate of the science baseline at time t using on-board metrology and guide star-determined orientation (it might be the best but it is still incorrect!)
    - $\mathbf{s}$ = a-priori source position at time $\mathbf{t}$
- Averaged regularized delay: d_{reg}
  - These regularized delays now can be averaged over the entire integration time (e.g., ~15 s to ~1 hr), **which is the main uncalibrated science data product of SIM**

    $$d_{reg} = \langle d_{reg}(t) \rangle$$

Delay equation fundamentals: 1

- Measured observable for each object for each ~15s-~1hr observation is regularized delay d_{reg}:

$$d_{reg} = (\underline{\mathbf{b}}_{reg} + \underline{\Delta \mathbf{b}}) \cdot (\underline{\mathbf{s}} + \underline{\Delta \mathbf{s}}) + C + FDE + ZE + \eta$$

- where:
  - $\underline{\mathbf{b}}_{reg}$ = regularized baseline (varies from tile to tile but is fixed for a tile)
  - $\underline{\mathbf{b}}_{reg} + \underline{\Delta \mathbf{b}}$ = average true baseline (varies from tile to tile but is fixed for a tile)
  - $\underline{\mathbf{s}}$ = a-priori source position (varies from source to source and time)
  - $\underline{\mathbf{s}} + \underline{\Delta \mathbf{s}}$ = actual source position (varies from source to source and time)
  - C = constant term (varies from tile to tile but is fixed for a tile)
  - FDE = field-dependent errors (varies with object location in tile and time)
  - ZE = sky-dependent zonal errors (varies with location in the sky)
  - η = random noise
- Fundamental astronomical quantity of interest is $\underline{\mathbf{b}}_{reg} \cdot \underline{\Delta \mathbf{s}}$:

$$\underline{\mathbf{b}}_{reg} \cdot \underline{\Delta \mathbf{s}} = d_{reg} - \underline{\mathbf{b}}_{reg} \cdot \underline{\mathbf{s}} - \langle \underline{\Delta \mathbf{b}} \rangle \cdot \underline{\mathbf{s}} - \langle C \rangle - \langle FDE \rangle - \langle ZE \rangle - \eta$$

- where $\langle x \rangle$ = calibration parameter x estimated using Grid star or Quasar observations
- Astrophysics for an object is done using $\underline{\mathbf{b}}_{reg} \cdot \underline{\Delta \mathbf{s}}$ values

Delay equation fundamentals: 2

SIM (Lite)

- Fundamental astronomical quantity of interest is $\underline{\mathbf{B}}.\underline{\mathbf{\Delta S}}$:

$$\underline{\mathbf{b}}_{\mathbf{reg}}.\ \underline{\mathbf{\Delta s}} = d_{reg} - \underline{\mathbf{b}}_{\mathbf{reg}}.\underline{\mathbf{s}}\ - <\underline{\mathbf{\Delta b}}>.\ \underline{\mathbf{s}}\ - <C>\ - <FDE>\ - <ZE> - \eta$$

- However, if project/NExScI does calibration correctly, then for all regularized delays:

$$\Delta d_{cal} = d_{cal} - \underline{\mathbf{b}}_{\mathbf{reg}}.\underline{\mathbf{s}} = \underline{\mathbf{b}}_{\mathbf{reg}}.\ \underline{\mathbf{\Delta s}} + \eta'$$

Where:

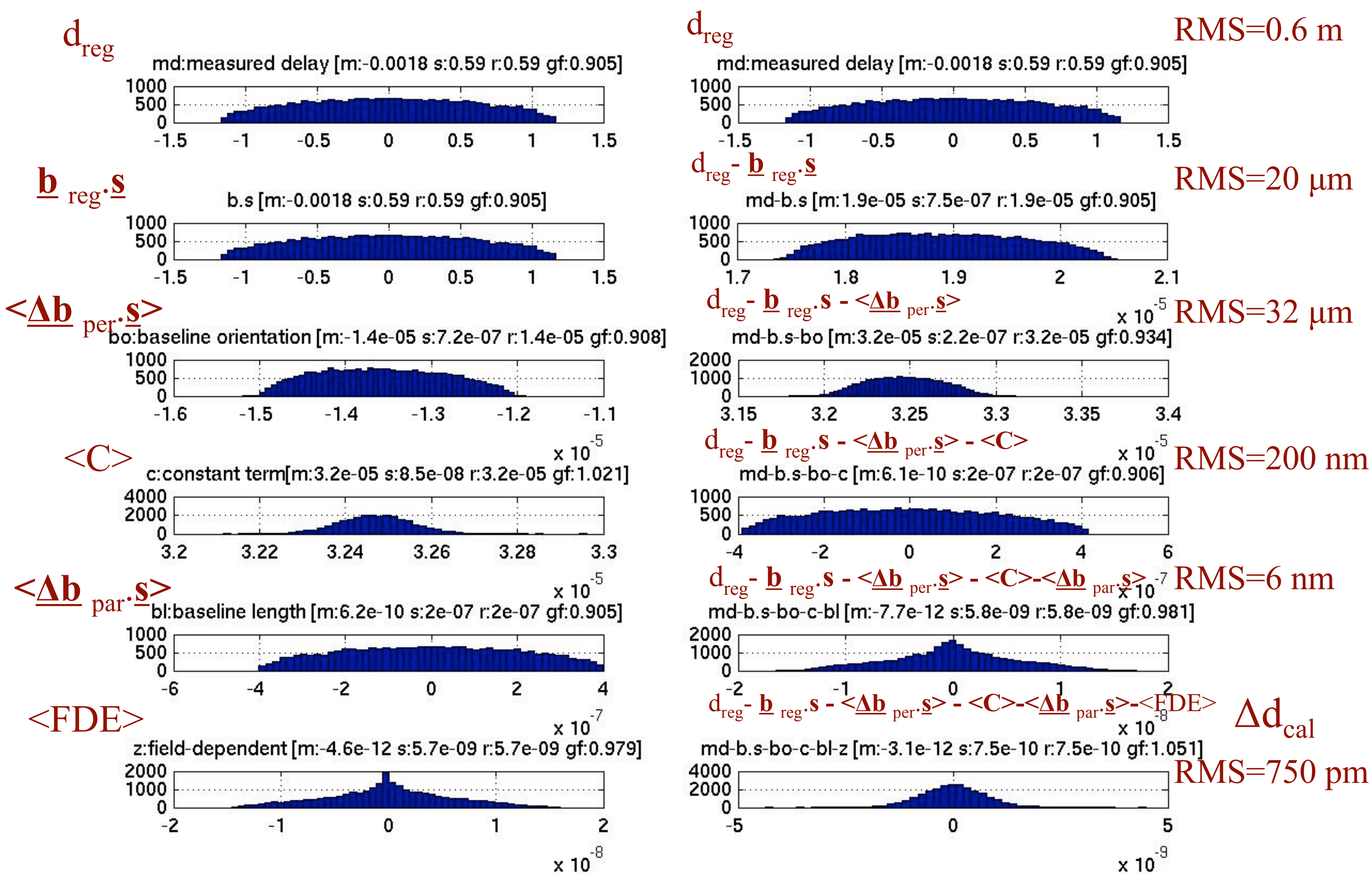
- $\Delta d_{cal} = d_{cal} - \underline{\mathbf{b}}_{\mathbf{reg}}.\underline{\mathbf{s}}$ = delay residual or residual delay [or 'regularized' delay by some!]
- d_{cal} = calibrated regularized delay = $d_{reg} - <\underline{\mathbf{\Delta b}}>.\ \underline{\mathbf{s}}\ - <C>\ - <FDE> - <ZE>$
- η' = effective random noise after calibration has taken place

  RMS(η')/RMS(η) = noise multiplier due to calibration

- Products delivered to astronomer: $d_{cal}(t)$, $\underline{\mathbf{b}}_{\mathbf{reg}}(t)$, [$\underline{\mathbf{s}}(t)$ (or equivalent)]
- What $\underline{\mathbf{b}}_{\mathbf{reg}}(t)$ do you need for your project?
  - How often do you need to observe your objects?
  - What baseline orientations would you like?
  - How does this need/request fit into schedule?
  - Does this need/request meet SIM-Lite spacecraft constraints
- What SNR ($=\underline{\mathbf{b}}_{\mathbf{reg}}.\ \underline{\mathbf{\Delta s}}/\eta'$) do you need for your project?

Delay equation fundamentals: example histograms

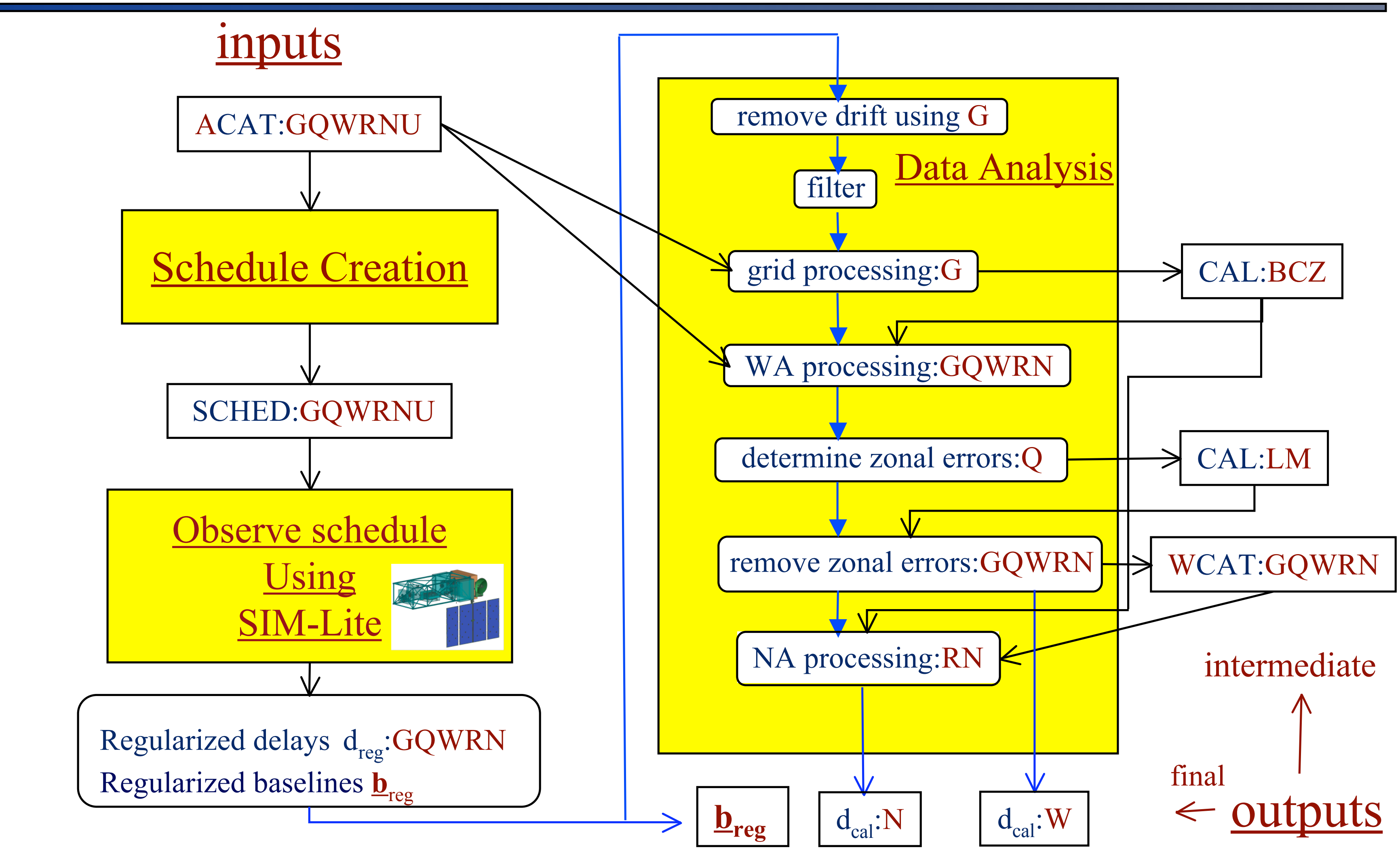
SIM (Lite)



- d_{reg} for 15-mag Quasars/9-m SIM Planet Quest/Δ**s**=0 simulation

Simplified SIM data flow block diagram

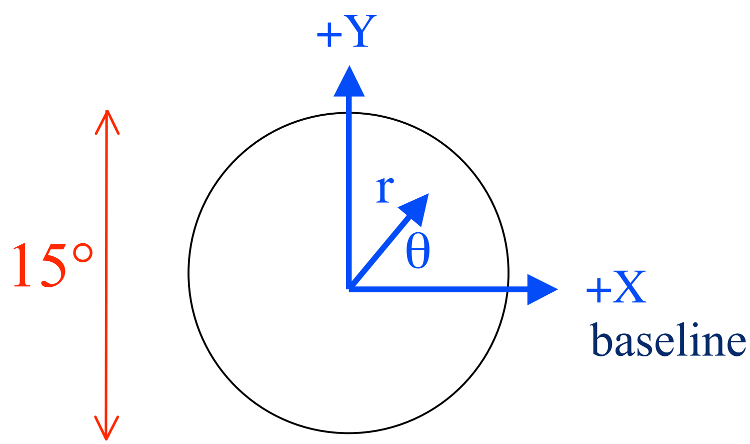
SIM (Lite)



- CAL=calibration data, CAT = star catalog
- Object: G=Grid, Q=Quasar,W=WA target, R=Reference, N=NA target, U = Guide
- A=a-priori, B=baseline orientation+length, C=constant term, Z=Zernike coeffs, LM=spherical harmonic coeffs
- d_{reg}= regularized delay, d_{cal} = calibrated regularized delay

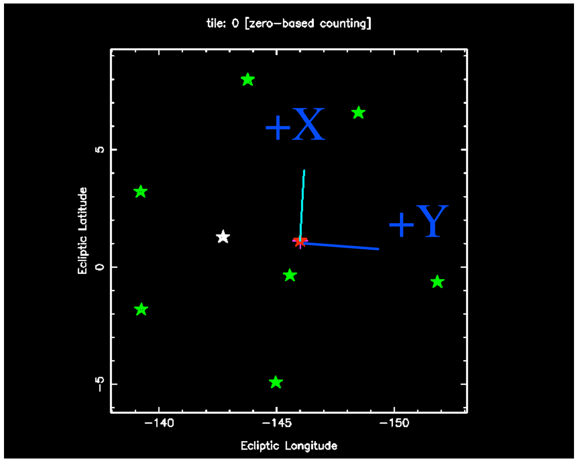
Field of Regard Co-ordinate System

Field of Regard (FOR) in Spacecraft Frame



- **Z** = **X** x **Y** = Tile center direction

Example tile:



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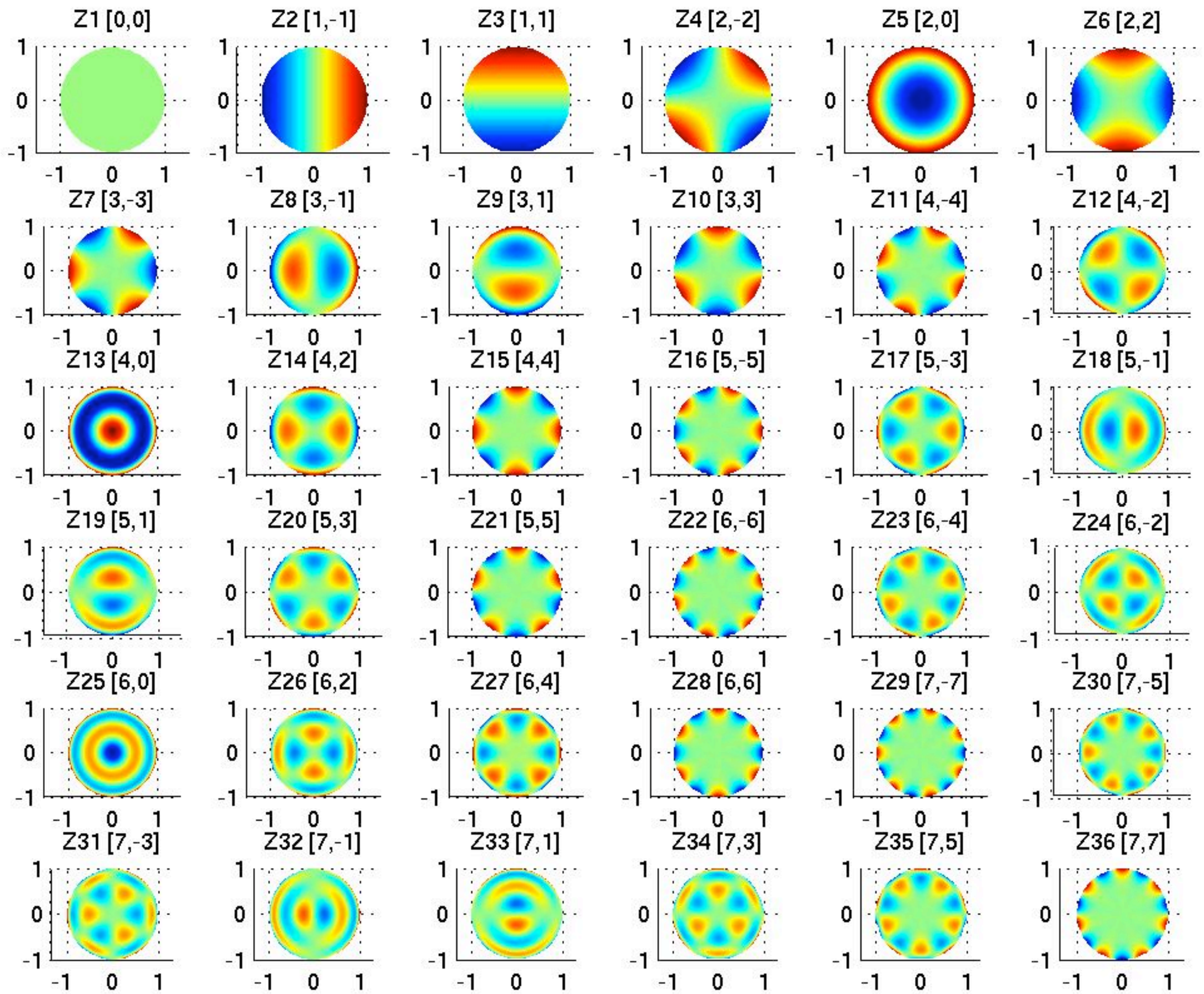
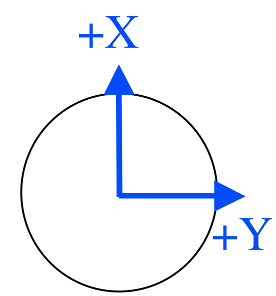
Use Zernike polynomials to represent FDEs

SIM (Lite)

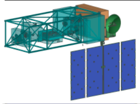
- FDEs can be represented as linear sum of Zernike polynomials



Zernike Polynomials up to seventh order in r



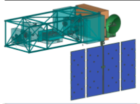
Methods of Calibrating Out Errors On Different Time Scales:1



SIM (Lite)

- Internal and external metrology gauge errors produce delay errors that are functions of
  - Time (time-dependent errors)
  - Position of the star in the field of regard (FDEs)
- Almost all SIM errors are time *de*pendent on some time scale
- Delay drift *on a few minute timescale* (of interest only for N targets)
  - Co-observe 4-5 Reference stars
  - Observe: $N\text{-}R_1\text{-}N\text{-}R_2\text{-}N\text{-}R_3\text{-}N\text{-}R_4\text{-}N\text{-}R_5\text{-}N$
  - Repeat in reverse R-order: $\text{-}R_5\text{-}N\text{-}R_4\text{-}N\text{-}R_3\text{-}N\text{-}R_2\text{-}N\text{-}R_1\text{-}N$
  - Solve and remove short-term drift by chopping adjacent N & R delays
- Delay drift between *observations within a single tile*
  - Main source of error is temporal drift in constant term C
  - Remove linear component of this C temporal drift by
    - Observing a single bright star at the beginning and end of the tile
    - This star can be at the center of the tile on the sky
  - NOTE: if ΔB_y and/or ΔB_z also drift significantly:
    - One or two more stars also could be re-observed and these drift in these components determined as well
    - These stars *cannot be at the center* of the tile (sample x,y dependence)

Methods of Calibrating Out Errors On Different Time Scales: 2



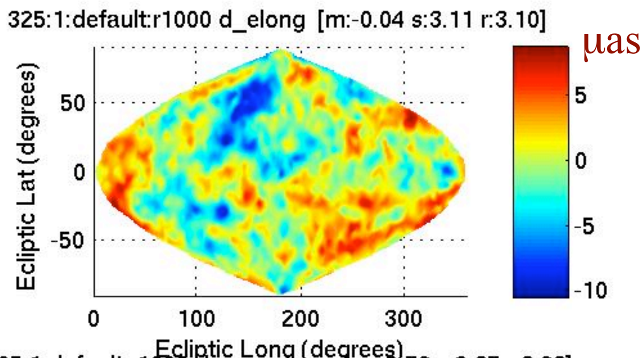
SIM (Lite)

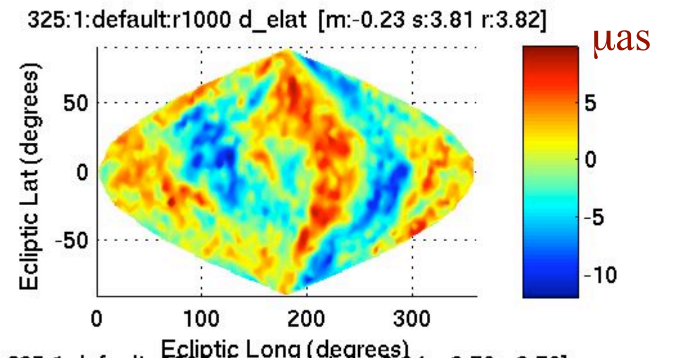
- Drifts in baseline parameters *between tiles*
  - ΔB_y, ΔB_z, and C are determined for each ~1hour tile
  - These instrumental parameters are solved for and removed during grid-processing (using a large matrix inversion)
  - This is equivalent to solving for Z_2, Z_5, and Z_1 in each tile
- Instrumental parameters that vary *only on time scales longer than a "solution interval"* (~100 or fewer tiles)
  - There are many other instrumental parameters that need to be calibrated out:
    - Baseline length ($=\Delta B_x = Z_3$)
    - Higher-order FDEs (Z_4, Z_6-Z_{15} and maybe higher)
  - PROBLEM: These all cannot be solved in every tile (too many parameters for the number of grid observations)
  - SOLUTION: Solve for those that are known to vary slowly only occasionally (i.e., ~500-1000 times) over the mission
- Global *zonal errors (ZEs) over the entire mission*
    - Incomplete sampling of the sky by the grid can produce systematic, correlated error patches on the sky
    - Proper motion (PM) & parallax (but not position) errors can be removed by
      - Observing 50-100 radio-quiet QSOs as part of the grid for ~1 minute each time, whenever they appear in a tile
      - QSOs should have ~0 PM and 0 parallax, allowing zonal errors to easily be fit to low-order vector and scalar spherical harmonics

Example of Zonal Errors (ZEs)

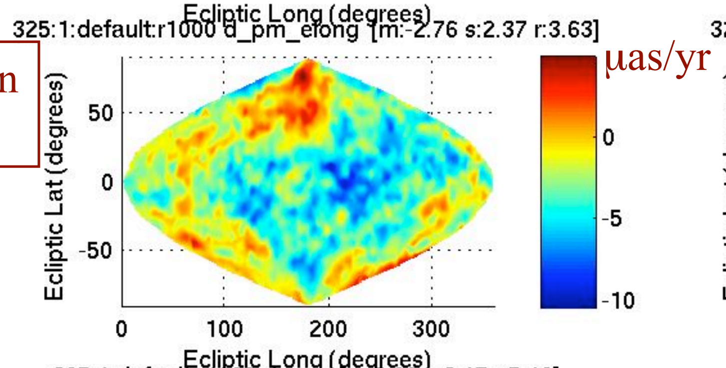
SIM (Lite)

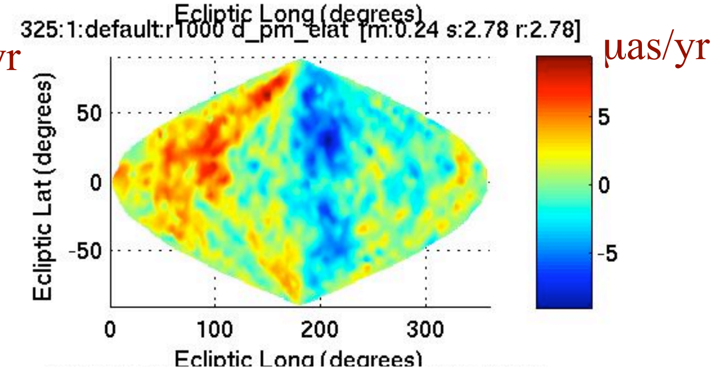
Position ZEs



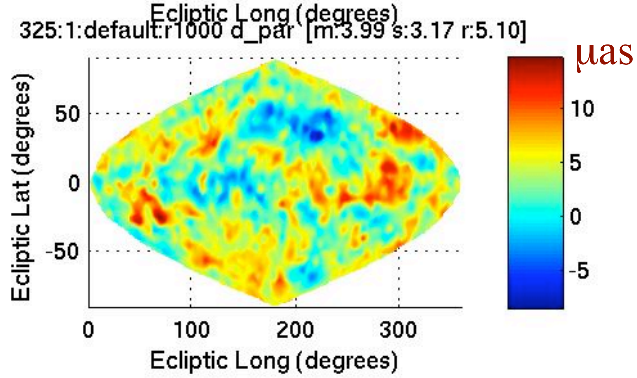


Proper Motion ZEs





Parallax ZEs



Summary and Questions

SIM (Lite)

- Project/NExScI creates d_{cal} from d_{reg}
- Large variety of errors are removed in this data processing
- $\Delta d_{cal} = d_{cal} - \underline{\mathbf{b}}_{\mathbf{reg}} . \underline{\mathbf{s}} = \underline{\mathbf{b}}_{\mathbf{reg}} . \underline{\mathbf{\Delta s}} + \eta'$
- Use of $d_{cal,}$ $\underline{\mathbf{b}}_{\mathbf{reg}}$, $\underline{\mathbf{s}}$ \ Δd_{cal} \astrophysics
  - What set of $\underline{\mathbf{b}}_{\mathbf{reg}}$ do you need?
  - What SNR ($= \underline{\mathbf{b}}_{\mathbf{reg}} . \underline{\mathbf{\Delta s}}/\eta'$) do you need?