Pointing Accuracy & Stability Recent JPL Experience

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December 4, 2002

With contributions by

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Overview

- *JPL Experiences*
- Overview of Pointing Definitions
- JPL Mission Experience
  - Cassini Experience
  - MRO Experience
  - SIRTF Experience

Recent JPL Experiences

- JPL has about 40 years of interplanetary missions experience.
- JPL missions include Flyby, Orbiters, Landers & Rovers.
- JPL is also involved with Earth orbiters & Observatories.
- Most JPL spacecrafts have been of the 3-axis stabilized with a few major exceptions.
  - Gallelio is a dual spin spacecraft; Spinner with a Scan Platform.
  - Mars Pathfinder was a spinner.
- Usually the Control systems for the 3-axis stabilized spacecraft includes:
  - Star Trackers & Inertial References Units for sensors.
  - Reaction Wheels and/or thrusters for actuations.
  - All hardware we utilize are commercially available
- Key to a successful 3-axis control system is the accompanying algorithm.

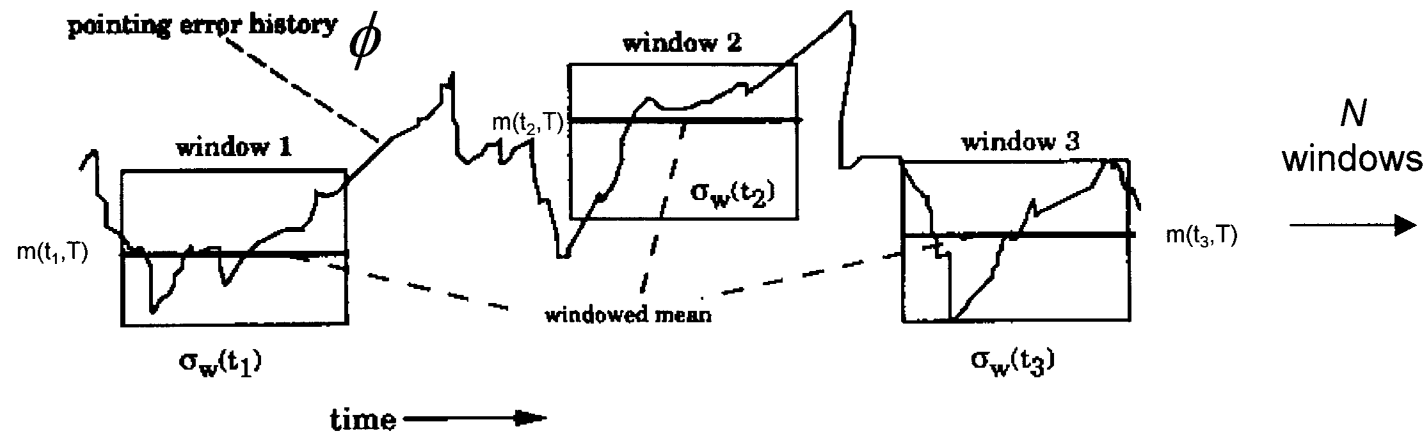
JPL Experiences

Missions	Pointing Accuracy Radial 99% [mrads]		Peak-to-peak Per-axis Excursion in Specified Time Windows [mrads]		
	control	Knowledge	0.5 Sec	1.0 Sec	12 Sec
Voyagers	3.0	1.8	0.01	0.02	0.24
Magellan	10.6	10.6	n/a	n/a	n/a
Galileo	2.9	0.9	0.007	0.014	0.17
Cassini	2.0	1.1	0.012	0.024	0.18
Mars Global Surveyor	7.3	3.7	0.25	3.0	36.0

Science Needs

- From the science point of view, there are three types of pointing:
  - Imaging science
  - Spectroscopy
  - Interferometric
- Common theme between all are requirements for,
  - Pointing Control Accuracy
    - Ability to place a target on a science instrument FOV
  - Pointing Stability
    - Ability to maintain the target within the SI FOV
  - Pointing Knowledge Accuracy
    - Ability to know the target/SI boresight after placement

Time-domain Pointing Stability Metric



Windowed mean value:

$$m(t,T) = \frac{1}{T}\int_{t}^{t+T} \phi(\tau)\,d\tau$$

Deviation from windowed mean value:

$$e(\tau,t,T) = \phi(\tau) - m(t,T)$$

$$\sigma_W^2(t,T) = \frac{1}{T}\int_{t}^{t+T} e^2(\tau,t,T)\,d\tau$$

RMS stability for window [t to t+T]:

$$\sigma_{wrms}^2(T) = \underset{N}{Expect}[\sigma_W^2(t,T)]$$

Cassini Pointing Stability Metric

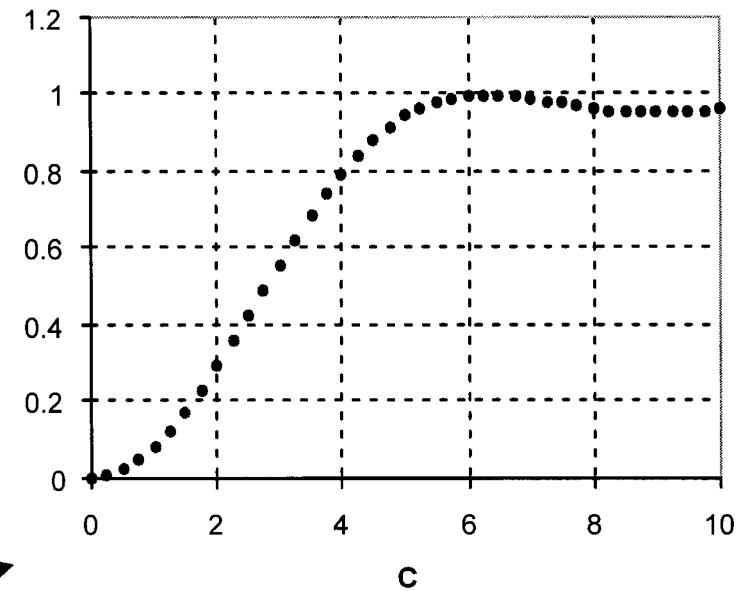
- *Cassini uses a frequency-weighted root-mean-squares pointing stability metric* (σ_{wrms}

$$\sigma^2_{wrms} = \int_0^\infty \Phi_{PSD}(f) \times W(f,T)d$$

where:

f	=	Frequency	[Hz]
T	=	Time window	[s]
$\phi(t)$	=	LOS motion	[rad]
$\Phi_{PSD}(f)$	=	PSD of $\phi(t)$	[rad²/Hz]
C	=	$2\pi fT$	[-]

$$W(C) = 1 - \frac{2(1-\cos C)}{C^2}$$



Cassini Pointing Performance

Allan Lee and Gene Hanover

Spacecraft Operations Office

October 9, 2001

Inertial Pointing Control Requirements

- The S/C inertial pointing control requirement is 2 mrads (radial 99%)
  - This requirement is applicable both when the S/C is quiescent and when it is being slewed with all per-axis rates ≤0.13 deg/s
- Predicted S/C inertial pointing control capabilities are:
  - 1.03 mrads (Quiescent, radial 99%)
  - 1.25 mrads (At rate, radial 99%)
    - In making these predictions, the following allocations were given to the S/C's attitude control errors:
      - 0.53 mrads (Quiescent, radial 99%)
      - 0.64 mrads (At rate, radial 99%)

Pointing Stability

[redacted]

- S/C pointing stability estimated using 2001-DOY-241 data

Exposure Time [sec]	Requirement†	Capability (Worst axis)
	$2\sigma_{wrms}$ per axis, μrads	
0.5	4	×
1	8	×
5	36	10
22	100	26
100	160	51
900	200	55
1200	220	56
3600	280	56

†See PD-600-004 (Revision E), Section 4213-7B.

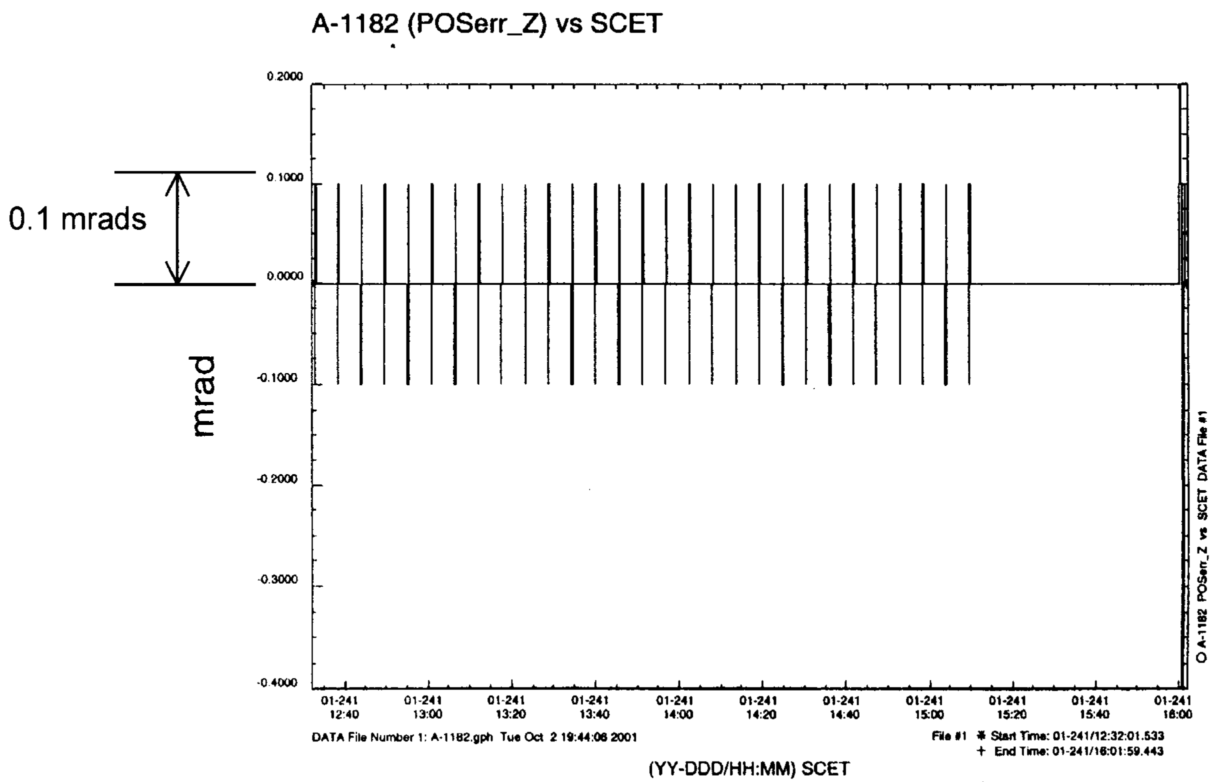
× Slow sampling rate prevented us from estimating these pointing stability.

Achieved Attitude Control Errors

[redacted]

- Between 2001-DOY-241:T12:32:01 and T16:00:00 (on Aug 29, 2001), the S/C is quiescent with all per-axis rates ≤0.01 deg/s:

$\varepsilon_X(t)$[1] = ±0.05 mrads, $\varepsilon_Y(t)$ = ±0.05 mrads, $\varepsilon_Z(t)$ = See below.



mrads

Allocation	0.53
Achieved	0.10

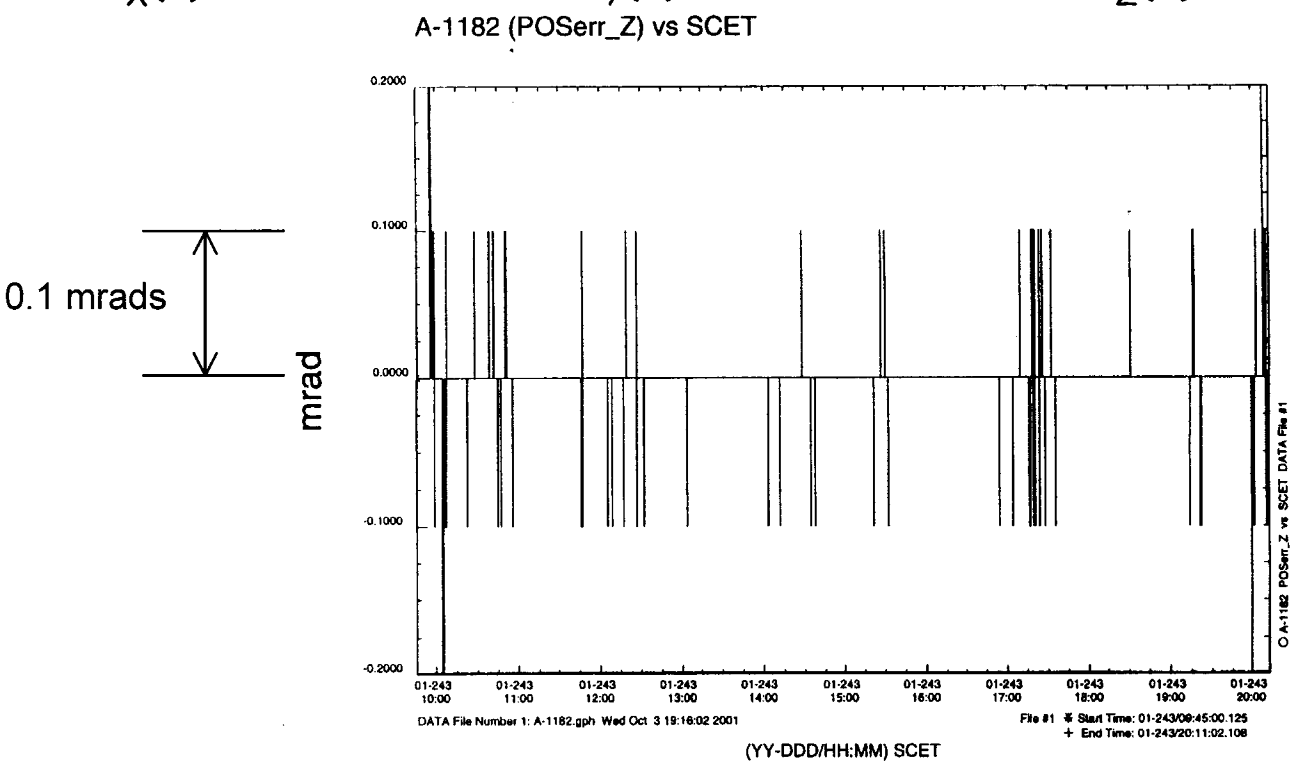
[1]Here, ε_i= i^{th}-axis attitude control error.

Achieved Attitude Control Errors

[redacted]

- Between 2001-DOY-243:T09:45:00 and T20:11:02 (on Aug 31, 2001), the S/C's [X, Y, Z] rates are bounded by [0.05, 0.08, 0.18] deg/s, respectively:

$\varepsilon_X(t)$[1] = ±0.1 mrads, $\varepsilon_Y(t)$ = ±0.30 mrads, $\varepsilon_Z(t)$ = See below.



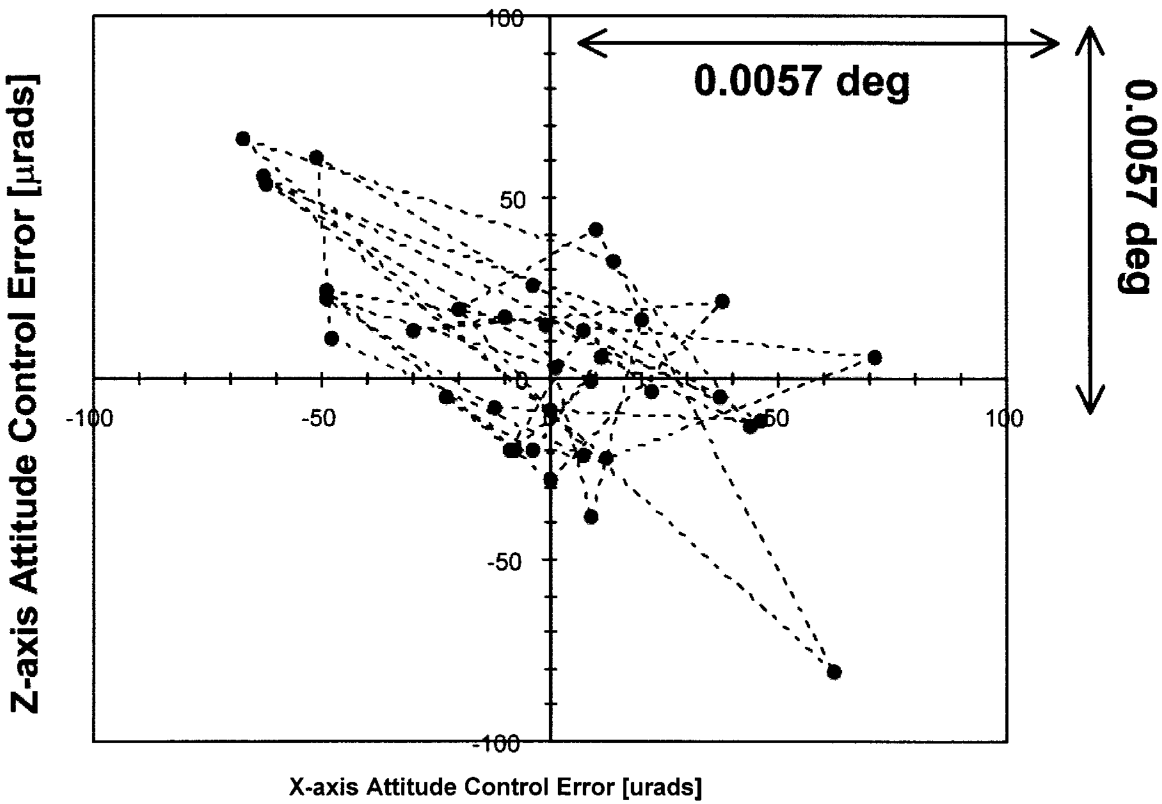
mrads

Allocation	0.64
Achieved	0.12

[1]Here, ε_i = i^{th}-axis attitude control error.

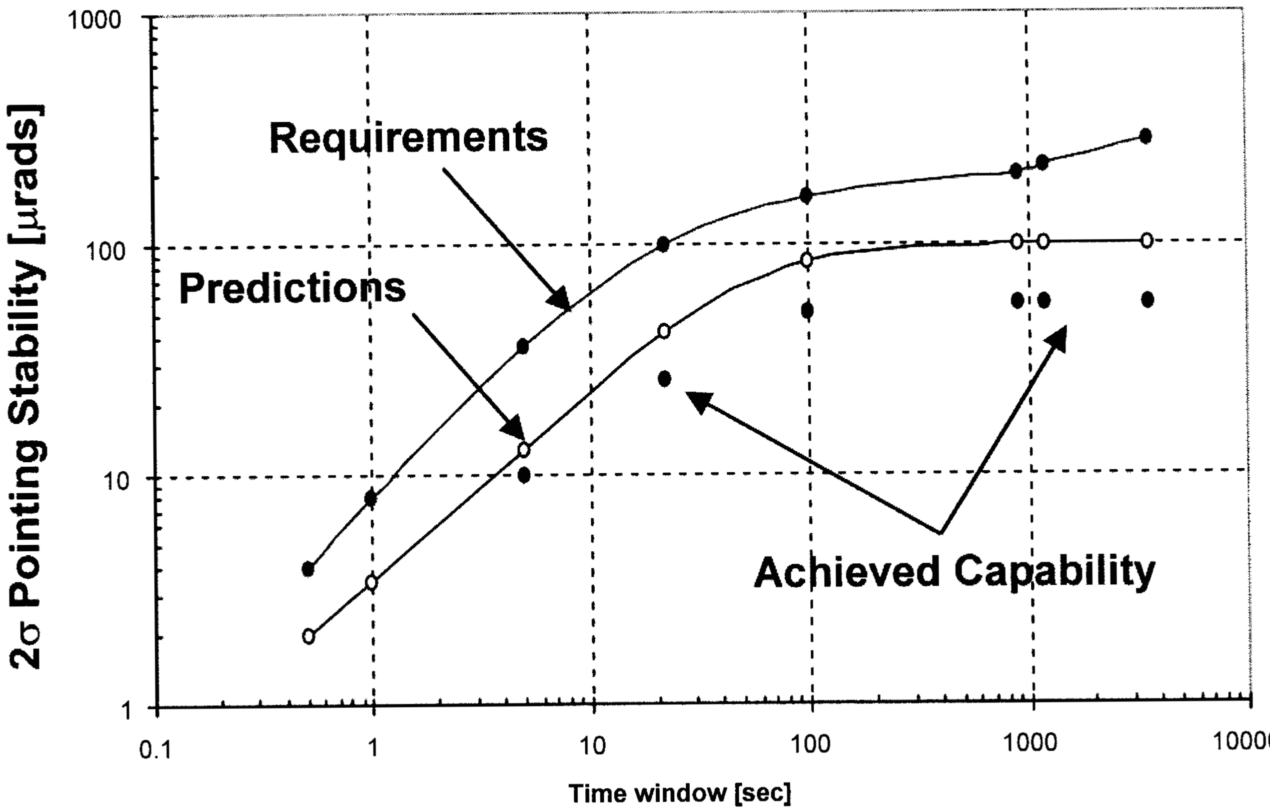
Achieved Pointing Stability

- Motion of the NEG_Y vector derived using 4 hours of telemetry data beginning on 2001-DOY-241/16:02:01†



†Only 1% of data are shown in figure. Per-axis pointing control errors are reconstructed using the S/C's per-axis rate estimates (A-1005 to A-1007) and the S/C's per-axis composite rate errors (A-1183 to A-1185).

Predicted S/C Pointing Stability



- Predictions made pre-launch are comparable to the achieved capabilities:
  - Predicted small-time window S/C pointing stabilities met requirements

MRO Pointing Stability

Requirements and Design Approach

Steven Lee
David Skulsky

Driving Requirements

- Pointing stability
  - Pointing stability requirement of 0.0015 mrad over 3 msec originally established to support high-resolution imaging
  - After selection, HiRISE team requested pointing stability improvement to 0.0032 mrad over 12 msec
- Momentum unloading: Reaction wheel assembly (RWA) momentum unloading limited to once every 48 hours to support accurate ephemeris prediction

Approaches to Improving Performance

- Design Changes
  - Increase momentum storage capacity of RWAs (100 Nms). Allows RWA speeds to be kept below 2400 rpm after 48 hours of momentum build-up.
  - Improve RWA balance with two balance iterations beyond vendor standard (25% better than qual test data). Reduces emitted imbalance disturbance.
  - Isolate MIMU (i.e. standard MIMU); requires attitude update from star tracker prior to imaging (after slews). Attenuates emitted disturbance due to MIMU dithering.
  - Implement various structural changes. Improves locations/transmissibility.
  - Provide local isolation of CRISM. Attenuates CRISM cryocooler higher harmonics (e.g. above 60-70 Hz).
- Operational Constraints
  - Pause Solar Array Motion during HiRISE observations
  - Pause MCS Motion during HiRISE observations

SIRTF
Pointing Control System

Tooraj Kia & Dave Bayard

System Level Key Requirements

FUNCTIONAL & PERFORMANCE REQUIREMENTS (FRD Sec 3.22)

FUNCTIONAL

- Acquisition
- Attitude Calibration
- Maneuvers
- Scans
- Inertial Stability
- Fault Management
- Safemode

PERFORMANCE

- 2.7 year lifetime
- Accuracy (1σ radial)
  coarse 5 a-s
  reposition 0.4 a-s
- Stability (1σ radial)
  0.3 a-s over 200 sec
  0.6 a-s over 500 sec
- Scan rates
  2 - 20 a-s/sec
- Freeze-frame stability during scan
  (1σ radial)
  0.7 a-s over 15 sec
  1.0 a-s over 150 sec
- Solar Object Track
  up to 1.0 a-s/sec
- Support
  Reconstruction
  1.4 a-s wrt J2000

EFFICIENCY

- Point to Point
  Maneuver
  180 deg in 1000s
  1 arcmin in 20 s
- On-board
  Star Catalog
- Autonomy
  - Resource
    Mgmnt

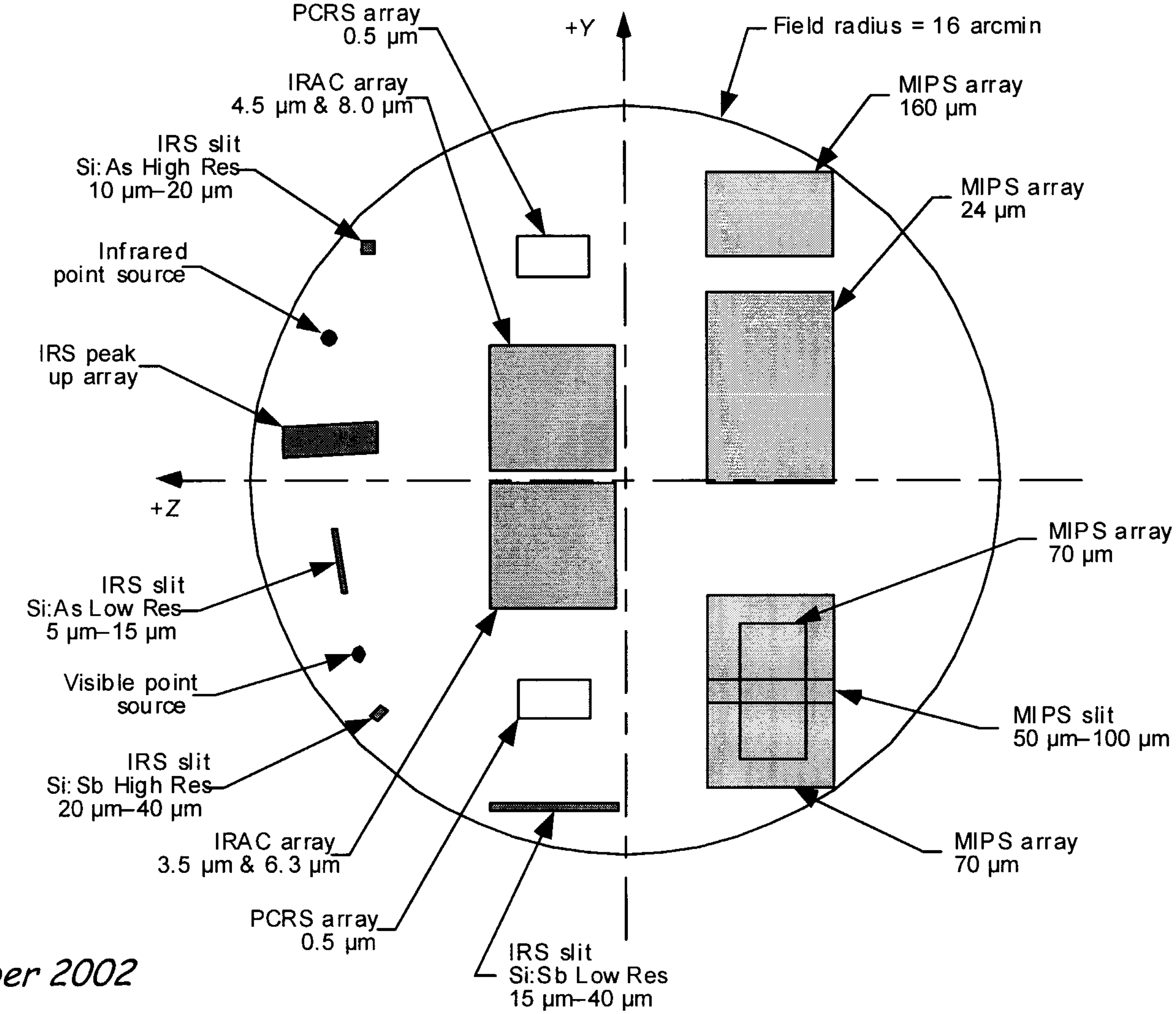
Science Observing Modes

- There are 7 observing modes:
  - IRAC Mapping and Photometry Mode
  - IRS Staring Mode
  - IRS Spectral Mapping Mode
  - MIPS Photometry and Superresolution Mode
  - MIPS Scan Map Mode
  - MIPS Spectral Energy Distribution (SED) Mode
  - MIPS Total Power Mode

- Then there is the reconstruction.

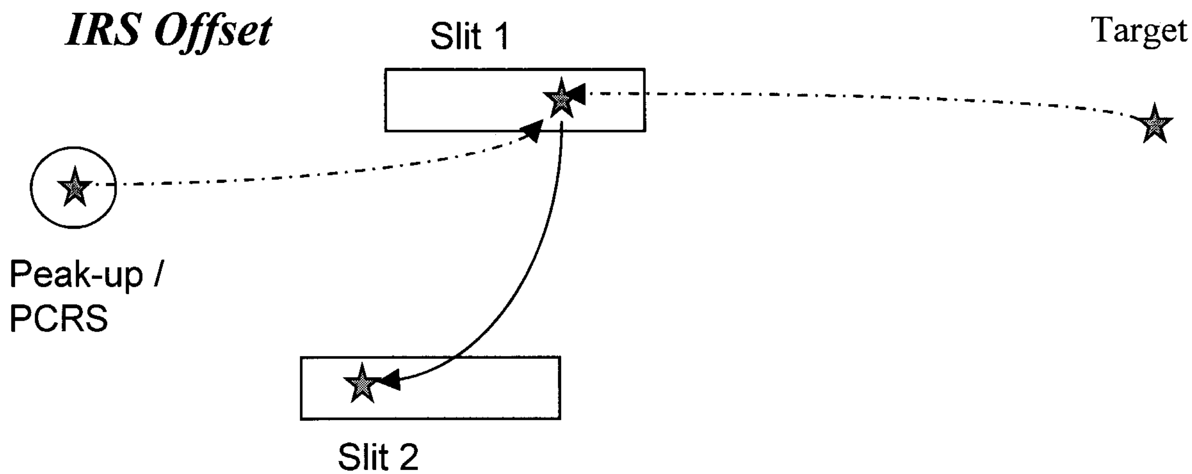
- The elements in all of them include one or more of pointing, scanning and stability.

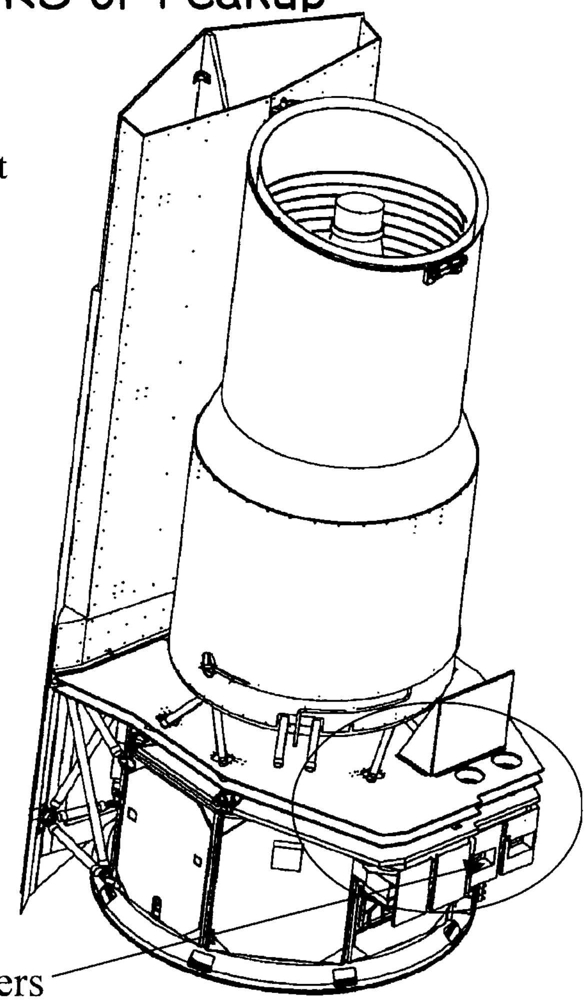
SIRTF Focal Plane



SIRTF Pointing Driving Requirement

- IRS performs precision measurements with PCRS or Peakup prior to target offset to desired aperture

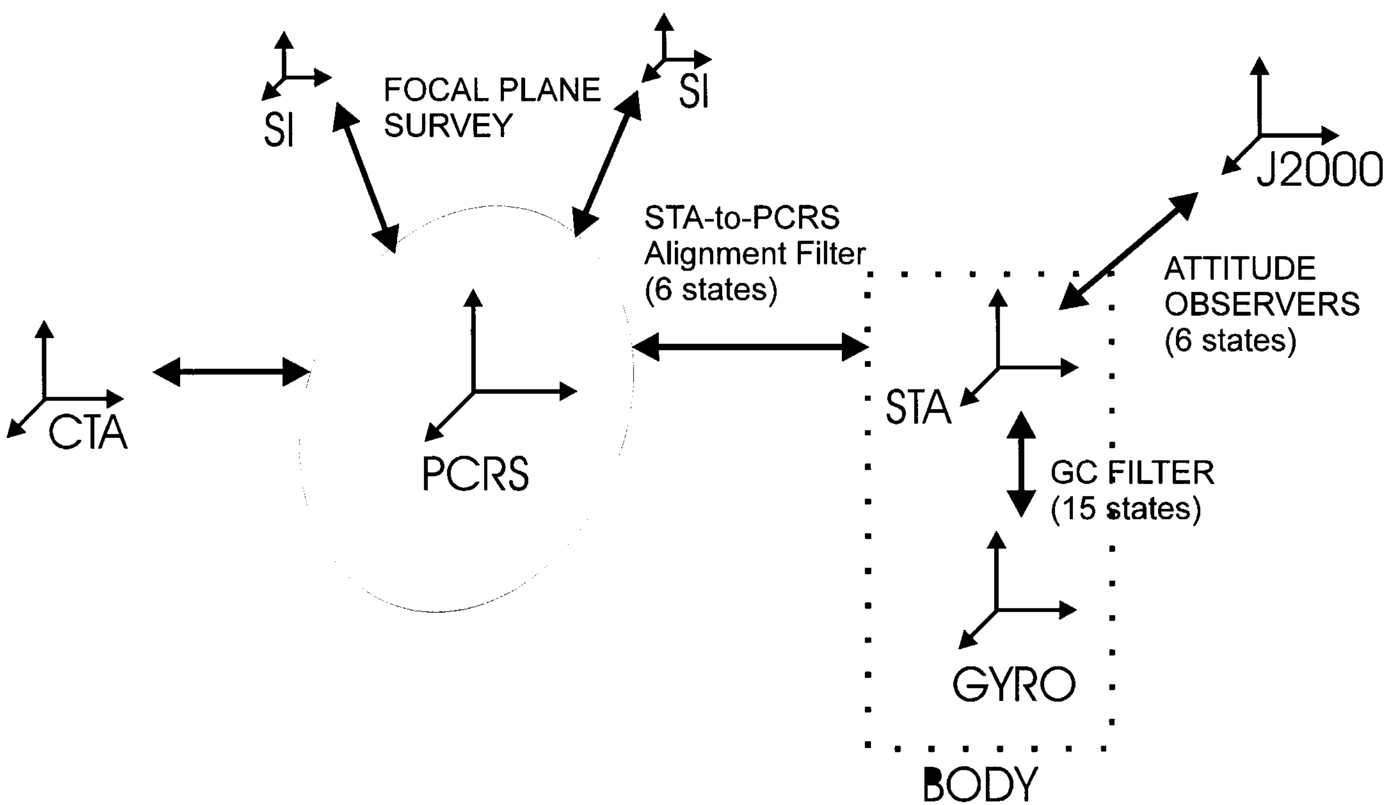




- Problem: PCS utilizes sensors to point that are not within the Cryo-Cooler.
  - The Telescope bore-sight drifts thermally and mechanically.

Calibration and Focal Plane Survey

- *RELEVANT FRAMES FOR SIRTF POINTING CONTROL*



SIRTF Incremental Pointing Error Budget

Incremental Acquisition & Placement
[redacted]
.56 as

RSS

Focal Plane Survey Geometric Error (0.30 as)
- •PU/TPF 0.14 as*[4]
- •TPF/SI 0.14 as*[5]
- •SI Internal (at slit) 0.14 as*[5]
- •STA/SI Roll Error
  - STA/TPF 0.08 as*[6]
  - TPF/SI 0.14 as*[7]
  - ATT Roll 0.06 as*[8]
  - (For companion targets only)

PU/PCRS Initial Peakup Accuracy (0.264 as)
- -PU internal 0.14 as*[4]
- -PU centroid 0.2 as
- -Companion knowledge 0.1 as*[10]

Incremental Pointing Bias in TPF Frame .395 as

SUM

Offset Execution Error (0.355 as)

Thermal-Mech*[9] 0.04 as

RSS

ATT Roll Error (0.06 as)
- • ATT Roll 0.06 as*[8]

Gyro Calibration Requirement
- • 100 Sec inertial hold Every 100 sec

Reposition Execution Error (0.32 as)
- •IRU Drift 0.22 as*[1]
- •IRU S/F 0.20 as *[2]
- •IRU Misalign 0.081 as*[3]
- •Observer settling on PU 0.07as

Handoff Execution Error (0.14 as)
- •Control Error 0.1 as
- •Attitude Jitter 0.07 as
- •Observer settling at slit).07 as (Due to STA bias shift)

*[1] Drift value of .001 as/sec over 157 seconds (37 turn plus 120 hand-off time). Verified separately via LMSC sim (assumes at least one 100 sec inertial hold for gyro bias calibration every 15 minutes)

*[2] 110=RSS(95,45) PPM combined linear and absolute scale factor is assumed over 30 arcmin turn. Verified separately via LMSC sim (assumes 30 min per day gyro cal). Per-axis value used as radial since error is orthogonal to misalignment

*[3] 45 microrad alignment is assumed over 30 arcmin turn. Verified separately via LMSC sim (assumes 30 min per day gyro cal). Per-axis value used as radial since error is orthogonal to scale factor

*[4] Focal plane survey allocation for Peak-up Arrays (will be zero if peaking up on PCRS)

*[5] Focal plane survey allocation for IRS Short-Hi slit

*[6] 6.5 as STA/TPF roll alignment accuracy over 30 arcmin turn. Verified separately via LMSC sim (assumes 1 PCRS calibration update every 8 hours)?

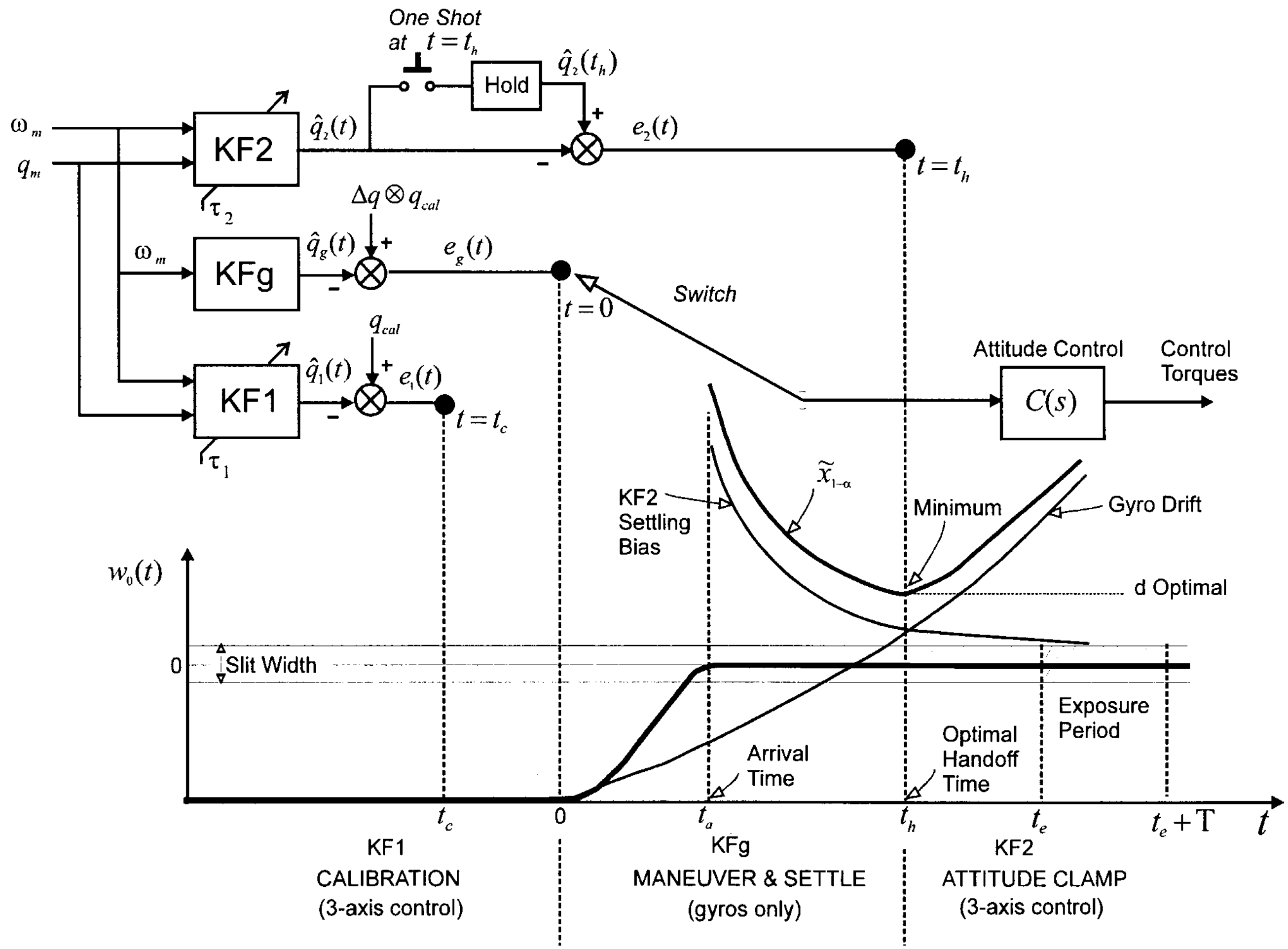
*[7] Focal plane survey allocation

*[8] 7[illegible] as STA roll accuracy ([illegible] 10410 R. Bezooijen) over 30 arcmin.

*[9] Thermal-Mechanical drift error of 0.04 as is calculated over 157 seconds of motion plus 500 seconds of observation.

*[10] Requirement on assumed knowledge (for companion targets only)

Reconfigurable Control

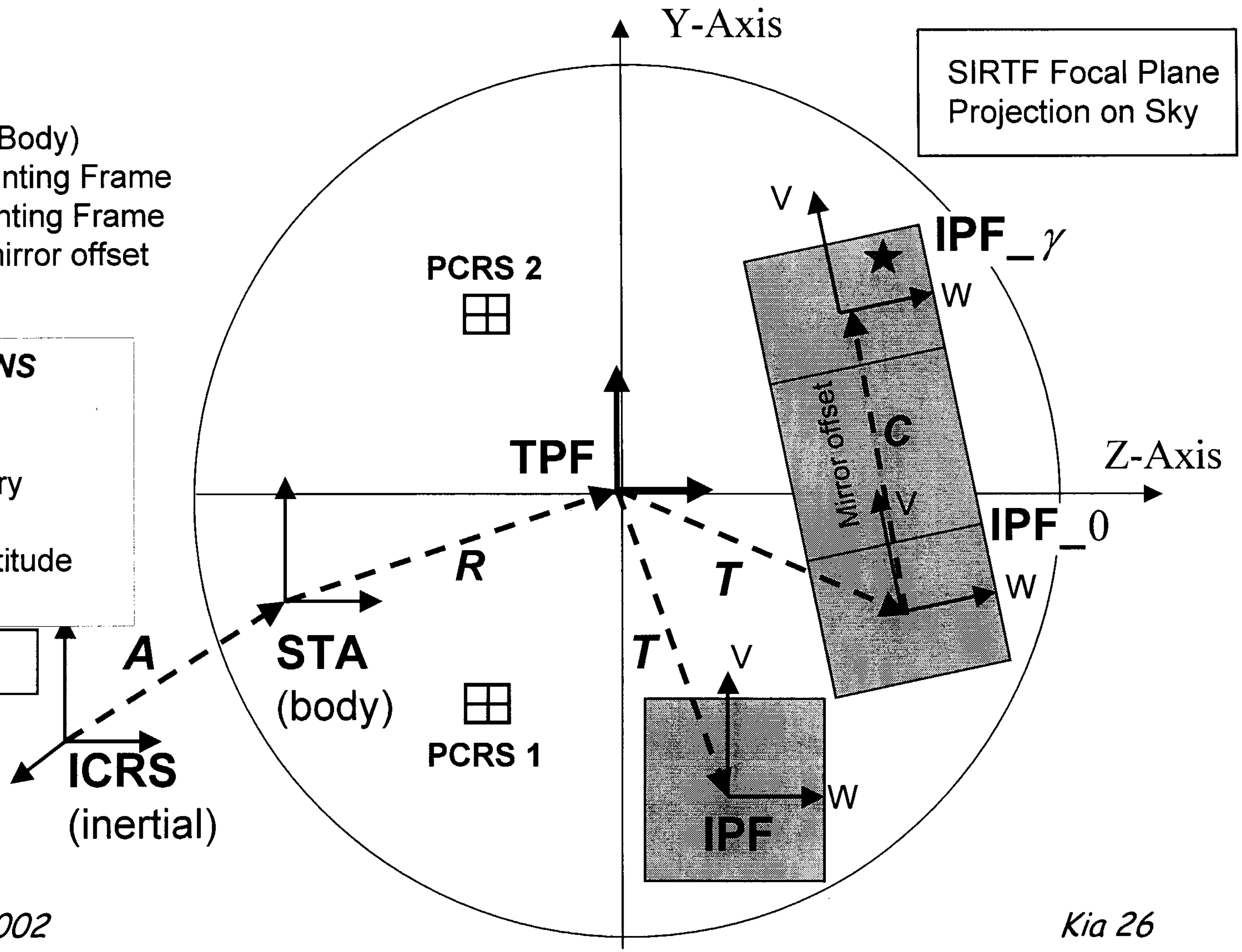


Observatory Pointing System Reference Frames and Transformations

FRAMES
ICRS - Inertial
STA - Star Tracker (Body)
TPF - Telescope Pointing Frame
IPF - Instrument Pointing Frame
IPF_γ - IPF with mirror offset

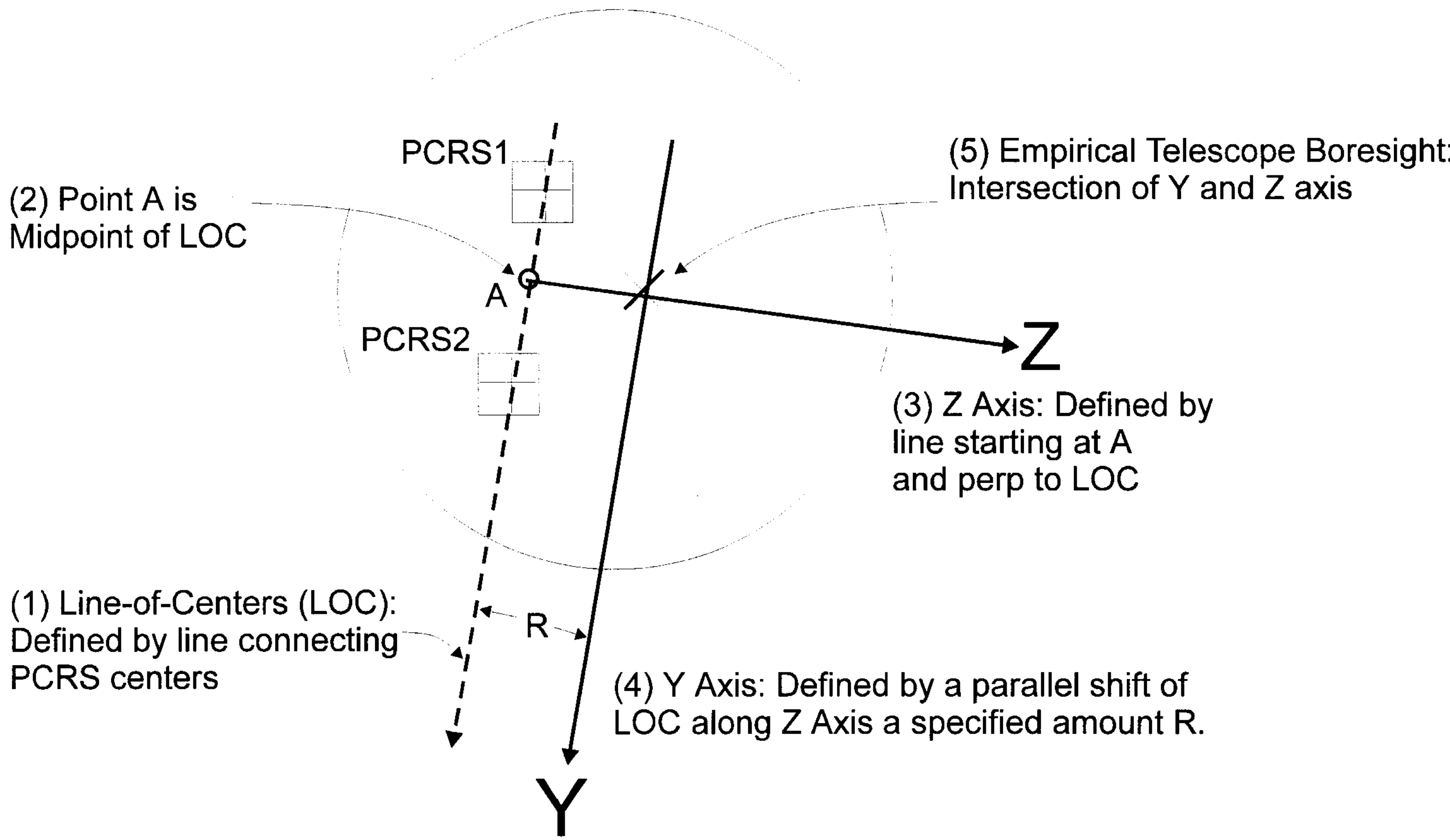
TRANSFORMATIONS
A – Body Attitude
R - Alignment
T - Frame Table Entry
C - Mirror Offset
A_o- Starting Body Attitude
G – Gyro offset

Note: $A = G * A_o$



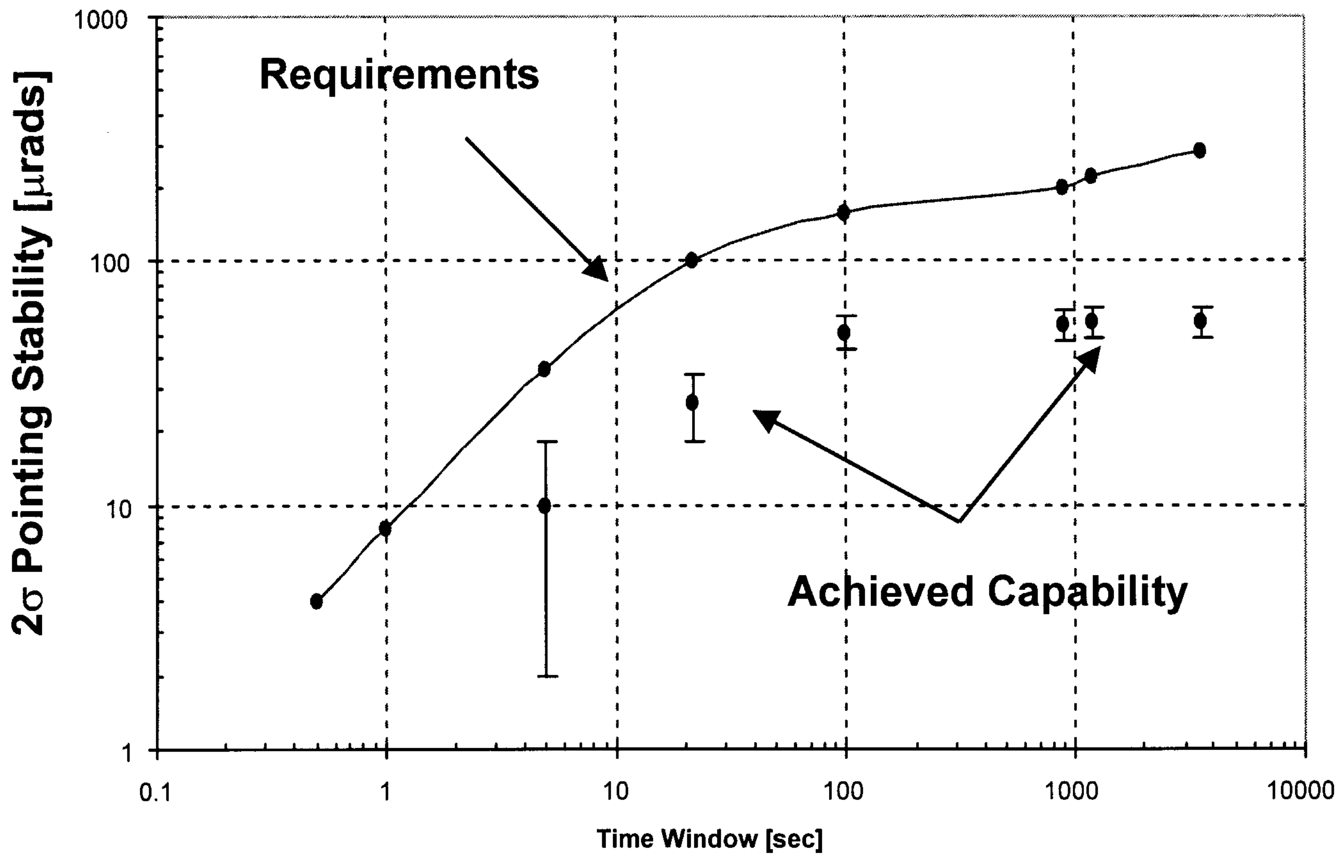
Calibration and Focal Plane Survey

PCRS DEFINED TELESCOPE POINTING FRAME - X,Y,Z



Backup Charts

S/C Pointing Stability:
[redacted]

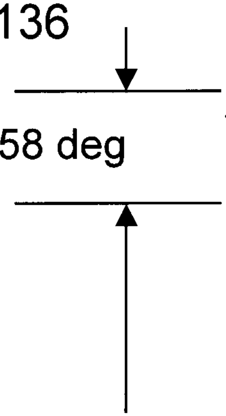


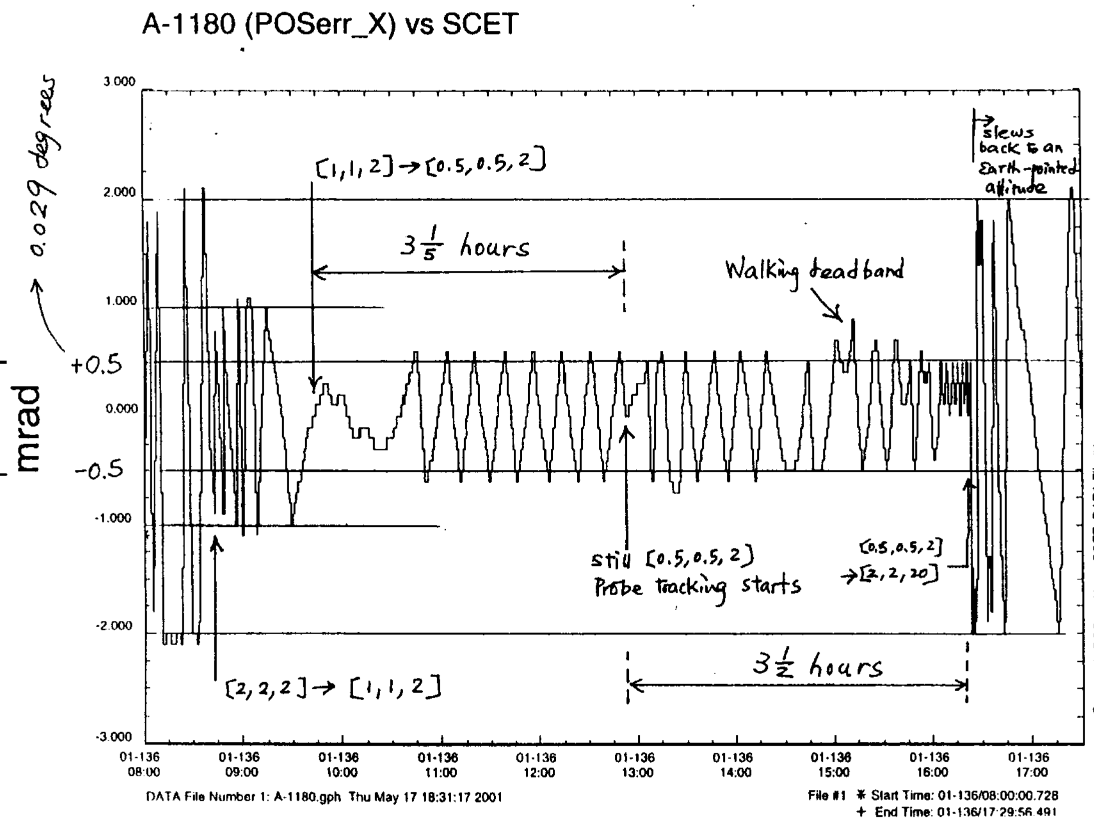
Thrusters-based Attitude [redacted]

- To support RADAR mapping at Titan: 2 mrads per X (and Y) axis
- To support Probe relay tracking: 0.5 mrads per X (and Y) axis

- Achieved performanc

The 0.5-mrads deadba
has been verified inflig
on 2001-DOY136





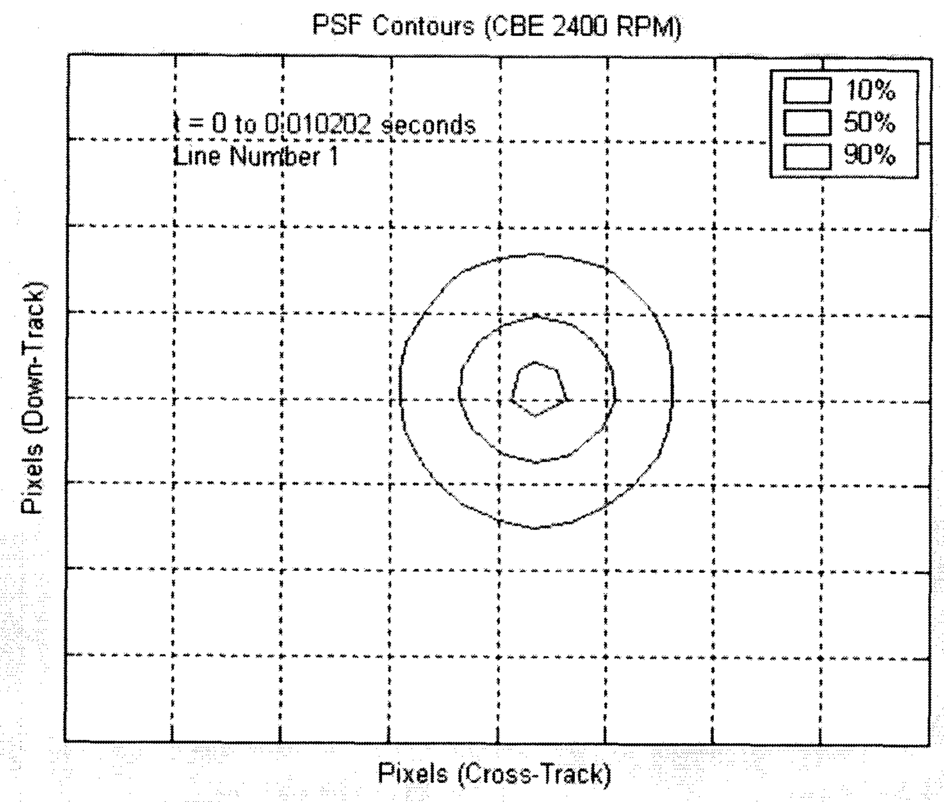
Summary of Performance

[redacted]

	CBE
Rate Error Contributors	*0.324*
IMU uncompensated bias drift	0.010
IMU scale factor error	0.003
S/C flex body dyn incl SHARAD	0.065
Propellant slosh	0.050
Target location errors incl terrain	0.007
Target timing errors	0.090
S/C ephem. errors on motion comp	0.017
S/C pointing errors on motion comp	0.004
ACS control loop rate error	0.300
Jitter Contributors (>20 hz)	*1.606*
RWA imbalance	0.467
IMU dither disturbance	0.150
CRISM gimbal drive	0.100
MCS gimbal drive	0.000
RWA motor disturbance	0.090
CRISM cryocooler	0.459
HGA gimbal drives	0.570
Solar array gimbal drives	0.000
Thermal snap	0.000
Alignment Contributors	*0.165*
Attitude control error w/r STU refn	0.080
Attitude knowledge error w/r STU	0.090
HiRISE alignment w/r STU after cal	0.075
HiRISE internal alignment after cal	0.075
HiRISE mech & thermal stability	0.040
Total (3-sigma)	*1.97*

All values in microrad

HiRISE PSF Animated Results

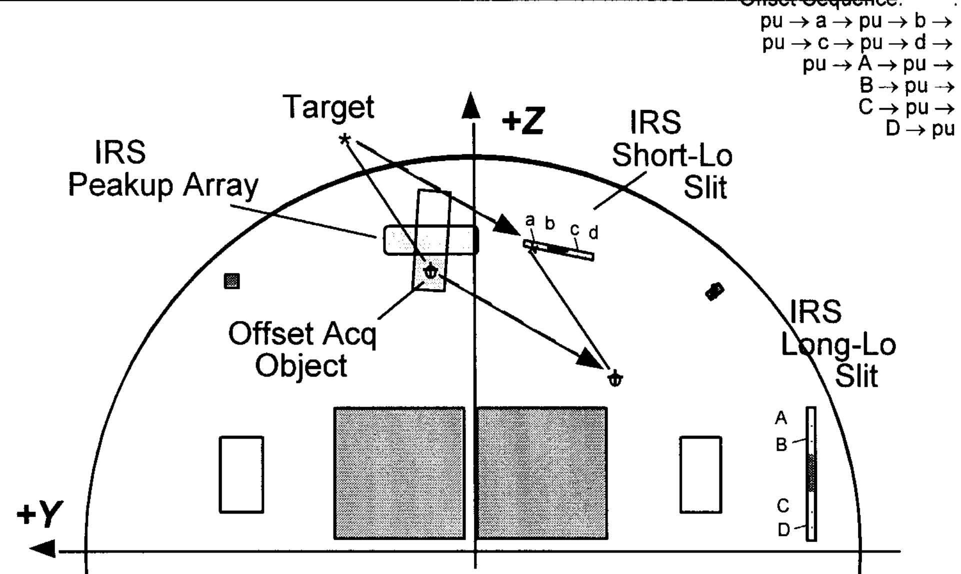


Representative Point Spread Function (PSF) Animation
Double-click image within slide show to run animation

IRS Staring Mode

Features

- High- or low-resolution Echelle spectroscopy over wavelength range 5-40 μm
- Four 128 x 128 pixel arrays, operating independently
- Frame times 1-32 sec; 8, 16, or 32 reads/ ramp (16 is AOT default); integration time built up via multiple ramps
- Peakup target acquisition using portion of short-low array, may be repeated during observation
- Low-resolution modules have 2 slit segments each (different wavelength ranges)
- Target placed on one of 2 subslit positions on slit
- 3 data collection modes (raw, sample-reset-sample, DCS), sample-up-the-ramp to be implemented later



Depicted: DRM Prog 4 offset target acquisition, placement on one of 2 subslit positions for each slit segment (Source: L. Armus, SSC/IPAC)

Examples

- DRM Prog 4 (galaxy redshifts): five 512-sec ramps at each of 2 subslit positions per slit segment, 2 segments for each low-resn module
- DRM Prog 3 (galaxy excitation mechs): three 512-sec ramps at each of 2 subslit positions per slit, for each high-resn module

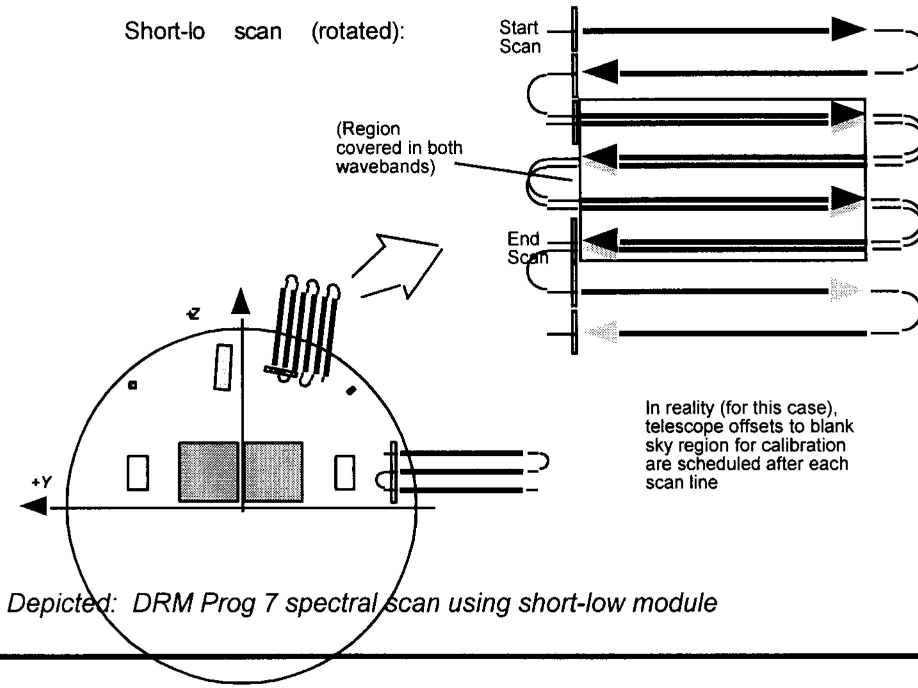
Effect on SC/PCS

- 0.7 arcsec PCS offset accuracy required to place target on slit, will assess pointing stability during each 2560-sec observation
- Hard Point 2 peakup or partial acq before each sub-slit obs, requires PCS coordination with SI computer
- Same as above, except 0.4 arcsec offset accuracy required for short-high slit, observations are 1536 sec, and Hard Point 1 peakup is used

IRS Spectral Mapping Mode

Features

- High- or low-resolution spectra of sources passing thru slit being scanned across sky in direction perpendicular to slit length, wavelength range 5-40 μm
- Four 128 x 128 pixel arrays, operating independently
- Frame times 1-32 sec; 8, 16, or 32 reads/ ramp (16 is AOT default); integration time built up via multiple scans
- Individual exposure (ramp) time corresponds to time a point source takes to cross half slit width
- Peakup target acquisition generally not required
- Extra scan legs required to cover field in both slit segment wavebands for low-resolution modules



Depicted: DRM Prog 7 spectral scan using short-low module

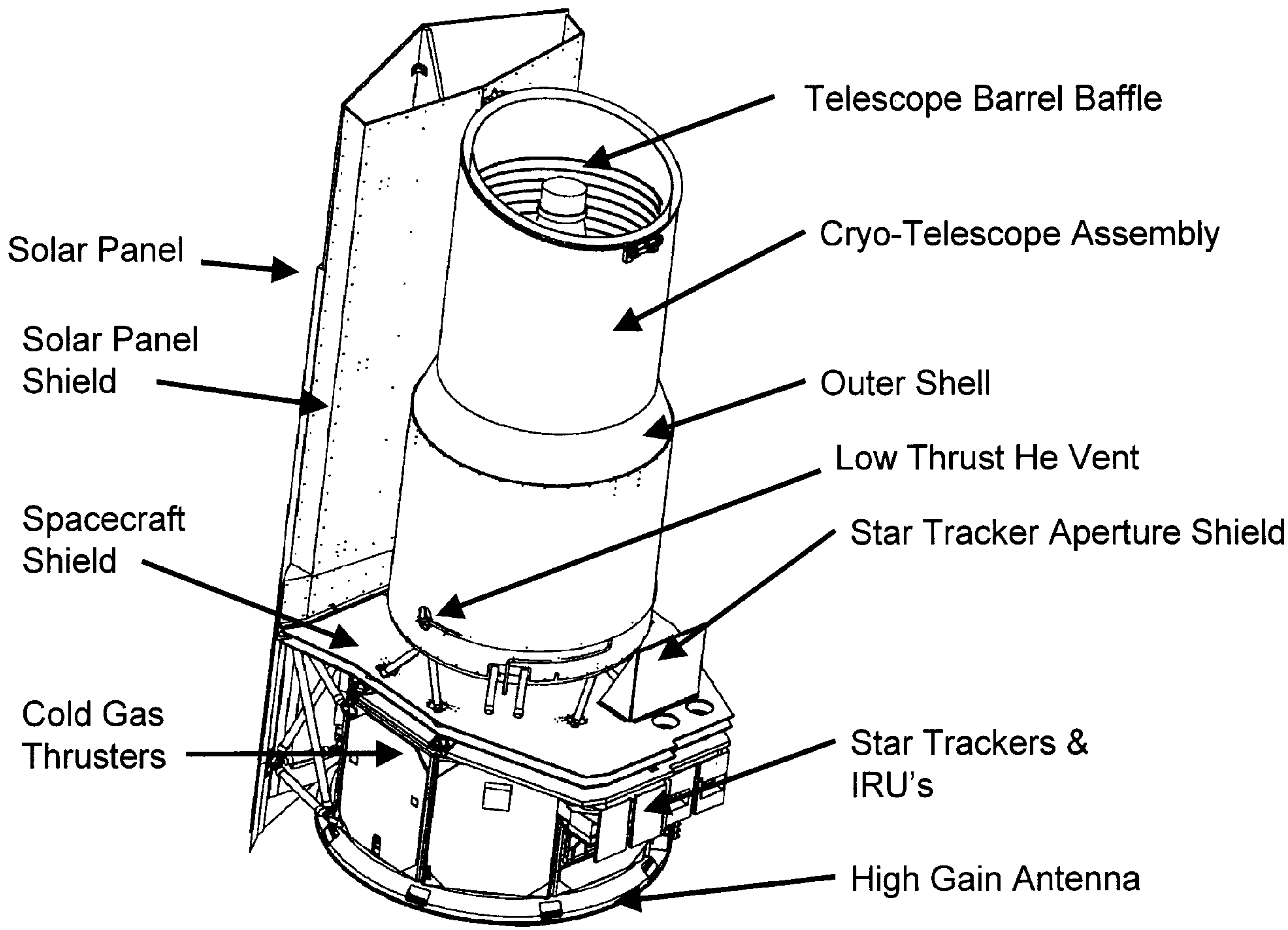
Examples

- DRM Prog 7 (cluster core spectral scan): six 300-arcsec scan legs with short-low module, offsets 95% of slit segment length, 16-sec exposures (1-sec frame times in raw mode, scan rate 0.11 arcsec/sec)
-

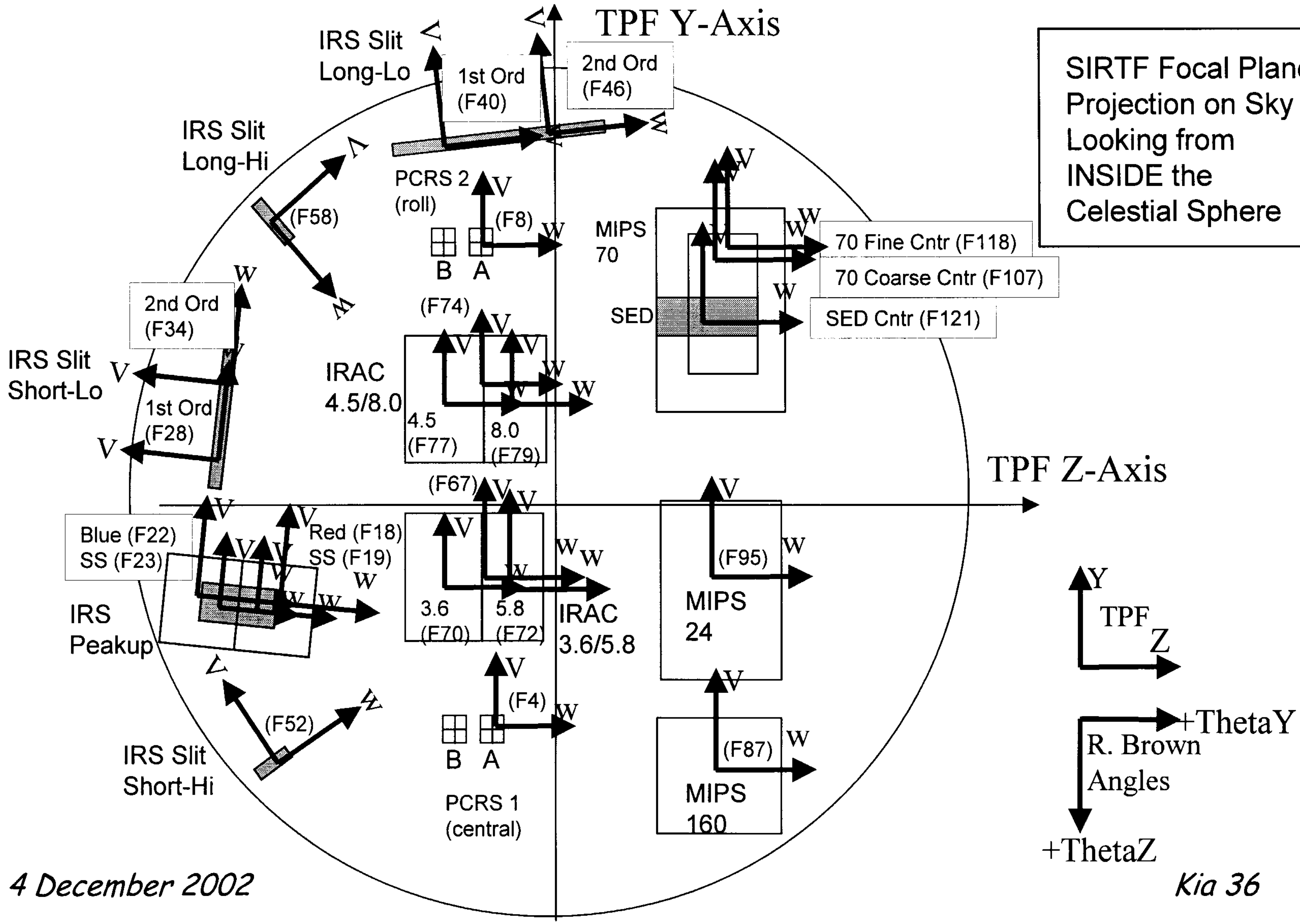
Effect on SC/PCS

- C&DH CPU loading (125 kbps compressed science data rate including blank frames each scan line)
- Timing coordination required between S/C and SI computers
- Slowest AOT allowable scan rate: 256 sec exposure time with short-low slit of 0.007 arcsec/.sec

Observatory External Configuration



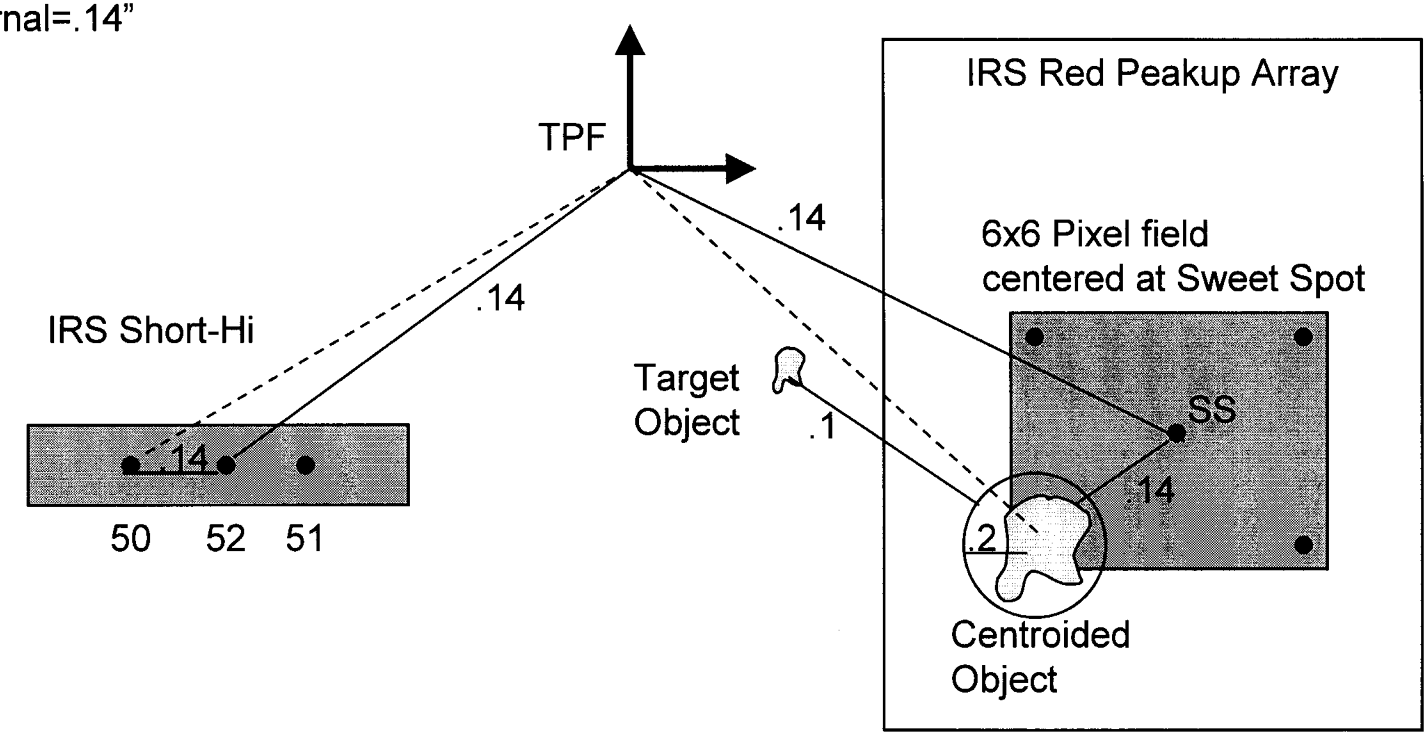
PRIME FRAMES



SIRTF Focal Plane Projection on Sky - Looking from INSIDE the Celestial Sphere

Incremental Pointing Errors

Peakup Error=.264" =(Peakup Internal=.14)+(Centroiding error=.2)+(Companion knowledge=.1) (RSS)
Peakup-to-IPF= .20" = (Peakup-to-TPF=.14)+(TPF-to-IPF=.14) (RSS)
S/I Internal=.14"



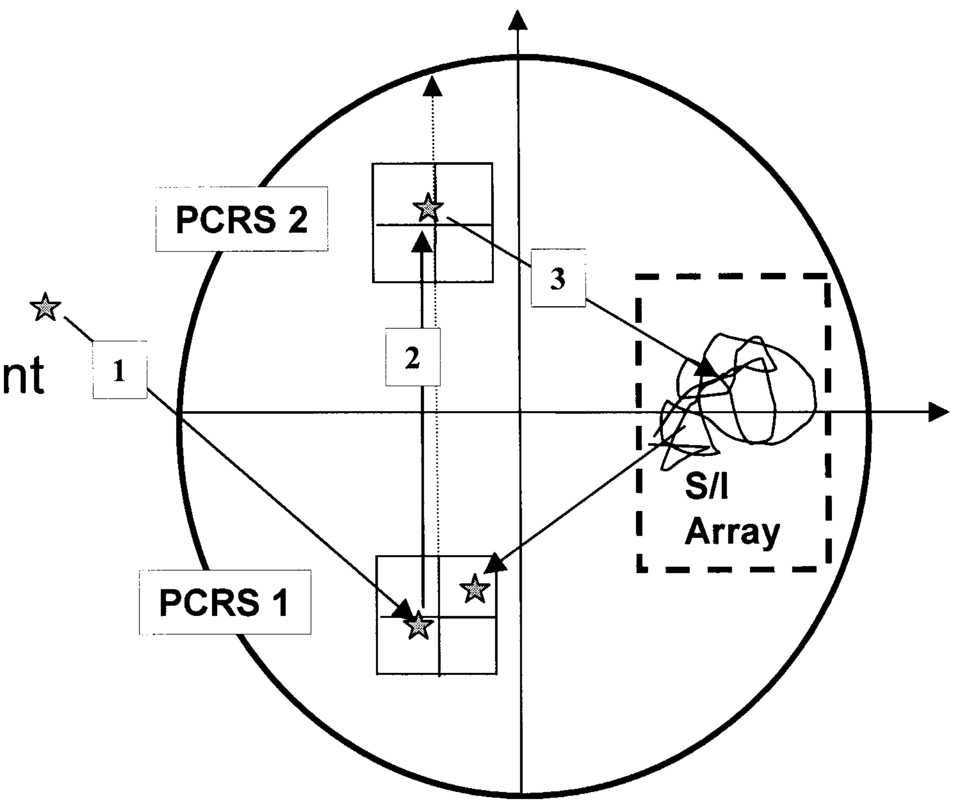
Note:
- Focal Plane Survey responsible for validation of all .14" numbers on this page
- Equivalent for dashed lines to be known to .20"=(.14)+(.14) (RSS)

SANDWICH MANEUVER

SANDWICH MANEUVER

(1) Centroid on PCRS1
(2) Centroid on PCRS2
(3) Centroid on Science Instrument
- time-tagged centroid 1
- ...
- time-tagged centroid N

(4) Centroid on PCRS1



- Allows precise attitude reconstruction relative to PCRS locations
- Allows calibration of a wide range of science array types