Pointing Stability of Hinode and Requirements for SOLAR-C (Option-B)

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Purpose:

Toward next Solar-C satellite with higher pointing-stability,

- Identify major sources for disturbances
- Assess the achievement of Hinode Satellite
- Raise Issues in realizing Solar-C (Option-B)

Contents:

1. Analysis on jitter ambient in the telemetry data of UFSS and IRU
   [low frequency regime \((10^{-4} \text{ Hz} < f < 10^{-1} \text{ Hz})\)]

2. Analysis on the jitter ambient from SOT with CT servo on/off
   [high frequency regime \((10^{-2} \text{ Hz} < f < 200 \text{ Hz})\)]

3. Requirements for Solar-C V.S. Performance of Hinode on-orbit
Image Stabilizing System on-board Hinode

Position Control Sensors and Correlation Tracker on board Hinode

- Ultra Fine Sun Sensor [UFSS (-A,-B)], \((10^{-5} \text{ Hz} < f < 10^{-1} \text{ Hz})\)
- Inertia Reference Unit [IRU (-A, -B1)], \((10^{-2} \text{ Hz} < f < 10^{-1} \text{ Hz})\)
- Correlation Tracker [SOT/CT], \((10^{-2} \text{ Hz} < f < 290 \text{ Hz})\)

- Specify the dominant disturbances in the jitter by Fourier Analysis
- Evaluate the amplitude of major disturbances (= Pointing Error)

※ IRU-A : FRIG floated rate integrating gyro (made by JAE)
IRU-B1: TDG tuned dry gyro (made by MPC)
1. Diagnostic data of UFSS/IRU
Time Profile: Telemetry data of UFSS and IRU

**UFSS-A+B**

- **X-axis**
- **Y-axis**

**Start Time (17-Dec-07 22:41:03)**

**IRU-A**

- **X-axis**
- **Y-axis**

**Start Time (20-Apr-09 08:41:05)**
Features and Major Sources for Disturbances in the jitter of UFSS:

- $f \sim 0.1 \text{ Hz}$: position sensor can control the disturbances with $f < 0.1 \text{ Hz}$
- $f < 10^{-3} \text{ Hz}$: orbital modulation + its higher frequency (2f, 4f, 6f …)
  
  [f $\sim 5 \times 10^{-3} \text{ Hz}$: unidentified (but, the contribution to the jitter is small)]
Features and Major Sources for Disturbances in the jitter of IRU:

- \( f \sim 0.1 \text{ Hz} \): position sensor can control the disturbances with \( f < 0.1 \text{ Hz} \)
- \( f < 10^{-3} \text{ Hz} \): orbital modulation + its higher frequency (2f, 4f, 6f …)

[no peak around \( f \sim 5 \times 10^{-3} \text{ Hz} \) which can be seen in UFSS data]

The characters of PSD in the case IRU are almost same as that in UFSS.
Characteristics in the long term variation:
- There is a seasonal variation in the orbital modulation as expected.
  : shade term (Apr. to Aug.) $\rightarrow$ large error, but it become smaller during Oct.-Jan.
- The modulation around 0.1 Hz increases secularly (we don’t know why...).
SOT Diagnostic data
Fourier Power Spectrum: SOT/CT - lower frequency band

CT Servo ON

- the disturbances are reduced clearly by CT in f < 10 Hz
- Peaks around 1.0 Hz are due to the polarization modulator rotating with period 1.6 sec
  - 0.625 Hz
  - 1.25 Hz (Stokes V)
  - 2.5 Hz (Stokes Q and U)

CT Servo OFF

※ Polarization modulator which is located in the optical path generates the modulations of the circular and linear polarization signals

Features:

- Polarization peaks due to polarization modulator

X-axis  Y-axis

0.625Hz  1.25Hz

0.625Hz  1.25Hz

※ Features:
- the disturbances are reduced clearly by CT in f < 10 Hz
- Peaks around 1.0 Hz are due to the polarization modulator rotating with period 1.6 sec
  - 0.625 Hz
  - 1.25 Hz (Stokes V)
  - 2.5 Hz (Stokes Q and U)

※ Polarization modulator which is located in the optical path generates the modulations of the circular and linear polarization signals
Features:
- 40-290Hz → a lot of peaks are generated due to the external disturbances (momentum wheel)
- The peak value of the error is typically $10^{-2}$ [arcsec]

20Hz (= cross over frequency)
The disturbances are reduced drastically at the lower frequency band than 20Hz (= cross over frequency).

SOT/CT show, even on-orbit, the performance expected before launching.
Requirements for Solar-C V.S. Performance of Hinode on-orbit

- Asses the achievement of Hinode Satellite
- Raise Issues in realizing Solar-C (Option-B)
The performance of image stabilization system on-board Hinode is excellent and meets the required ability even on-orbit.
Requirements for Solar-C and Performance of Hinode on-orbit
(for pointing error)

1) Pointing Error in X-axis is used for CT
2) Acceptable level is the 1/3 of requirements and is filled by the color

Issues:
- The performance of Hinode around 0.1 Hz does not meet the requirement for X-ray (NI)
- The performance of Hinode around 100 Hz does not meet the ability for UV-Vis-NIR
Requirements for Solar-C and Performance of Hinode on-orbit

1) Pointing Error in X-axis is used for CT
2) Acceptable level is the 1/3 of requirements and is filled by the color

- UFSS performance
- IRU performance
- CT (servo off)
- CT (servo on)
If UV spectrograph with 0.2" spatial resolution is assumed, the required ability for VUV/EUV become more severe (0.3 arcsec $\rightarrow$ 0.05 arcsec).
In the band $f > 20\text{Hz}$, we should reduce the disturbances generated by MW or extend the cross over frequency up to $300\text{ Hz}$ in order to meets the requirement.

The major disturbance source in UFSS/IRU is the orbital modulations in the band $f < 10^{-3}\text{Hz}$. They are generated due to the change of thermal environment, not due to the characteristics of the position control sensors.

We should consider seriously the thermal structure of Solar-C

In the band $0.01\text{Hz} < f < 1\text{Hz}$, the performance meets the required abilities for UV-Vis-NIR, VUV/EUV and X-ray (GI) at least, but not for X-ray (NI).

CT would be needed for X-ray (NI) with required ability

CT would be needed for UV spectrograph with $0.2''$ spatial resolution

The disturbances in $\sim 0.1\text{ Hz}$ seems to have serious impacts on Solar-C. It must be reduced in designing the position control sensor for Solar-C.
Please keep this viewgraph in your mind!

1) Pointing Error in X-axis is used for CT
2) Acceptable level is the 1/3 of requirements and is filled by the color

when you explore the science target for Solar-C
Appendix
We analyze the jitter in telemetry data of UFSS, IRU, and diagnostic data of SOT/CT.

- **UFSS, IRU:**
  - 40 data sets [from November 2006 to April 2009 (full disk only)]
  - Sampling: 0.5 sec (successive data more than 9 hours)
  - Drift component is removed (by using the linear fitting)

- **SOT/CT:**
  - Diagnostic data of CT servo on/off [focus on Dec. 2007]
  - Sampling: 580 Hz (df = 0.5 Hz for averaging)

- Specify the distinguished peak from Fourier Power Spectrum (PSD)
- Evaluate the amplitude of the major disturbances (= Pointing Error)

※) IRU-A: FRIG floated rate integrating gyro (made by JAE),
   IRU-B1: TDG tuned dry gyro (made by MPC)
Evaluation Methods for Disturbances

- Thick line: By using high pass filter, we integrate PSD in the lower frequency regime
- Symbol: By picking the distinguished peak from PSD up, we integrate the peak value around peak frequency

Pointing error with high pass filter gives the upper limit of the error
Short term variation of higher frequency peaks

Short term variation of higher frequency peaks around 100Hz ($t < 20$sec)

- no remarkable variation in short term
Long term variation for pointing error in CT Servo off

- 20061027
- 20061108
- 20070316
- 20071215
- 20071216
PSD from diagnostic data in CT servo off (100sec data)

\[ E_x = 0.032 \text{ [arcsec]} \]
\[ E_y = 0.045 \text{ [arcsec]} \]

20061108
Secular swing for the disturbances in the higher frequency

Higher frequency disturbances tend to increase secularly.

The peaks around 150Hz (due to IRU) and 180Hz swing remarkably.
Secular swing for the disturbances in the lower frequency band.

- There is no significant secular variation in lower frequency band.
Comment on Solar-C VUV/EUV

UV spectrograph in Solar-C can really achieve 0.2” resolution?

We need CT in UV spectrograph for realizing 0.2” pointing resolution.
Appendix 2: Data Sets (UFSS/IRU)
UFSS-A+B: (2008-4-22)
IRU-A: (2008-4-22)

- IRU_A X
  - y-axis: (arcsec)
  - x-axis: 14:00 to 20:00
  - Start Time: 22-Apr-08 12:48:26

- IRU_A X PSD
  - y-axis: (arcsec²/Hz)
  - x-axis: f (Hz)

- IRU_A X Jitter
  - y-axis: (arcsec, Jg)
  - x-axis: f (Hz)

- IRU_A Y
  - y-axis: (arcsec)
  - x-axis: 14:00 to 20:00
  - Start Time: 22-Apr-08 12:48:26

- IRU_A Y PSD
  - y-axis: (arcsec²/Hz)
  - x-axis: f (Hz)

- IRU_A Y Jitter
  - y-axis: (arcsec, Jg)
  - x-axis: f (Hz)
UFSS-B: (2008-12-20)
UFSS-A+B: (2008-12-20)

UFSS_A+B X

UFSS_A+B X PSD

UFSS_A+B X Jitter

UFSS_A+B Y

UFSS_A+B Y PSD

UFSS_A+B Y Jitter
Appendix 3: data sets (SOT/CT)
# Summary of data analyzed

<table>
<thead>
<tr>
<th>Data Set 1</th>
<th>Data Set 2</th>
<th>Data Set 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>on/off</strong></td>
<td>servo on</td>
<td>servo on</td>
</tr>
<tr>
<td>Date</td>
<td>2006/10/31</td>
<td>2006/10/27</td>
</tr>
<tr>
<td>$T_d$ [sec]</td>
<td>1687</td>
<td>256</td>
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<tr>
<td>$\Delta f_1$ [Hz]</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$\Delta f_2$ [Hz]</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>Date</td>
<td>2007/12/15</td>
<td>2007/12/15</td>
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<tr>
<td>$T_d$ [sec]</td>
<td>30.0</td>
<td>1724</td>
</tr>
<tr>
<td>$\Delta f_1$ [Hz]</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$\Delta f_2$ [Hz]</td>
<td>0.025</td>
<td>0.025</td>
</tr>
</tbody>
</table>

- $T_d$ · · · duration of data
- $\Delta f_1$ · · · frequency resolution for analyzing higher frequency band
- $\Delta f_2$ · · · frequency resolution for analyzing lower frequency band
Data Set 1
Figure 1: normal plot

\[ \Delta f = 0.5\text{Hz} \]

![Graph showing frequency response with labels for IRU-A (113Hz) and IRU-B (155Hz).]
Figure 2: logarithm plot of Fig.1

$\Delta f = 0.5$Hz

Servo on (20061031)

Servo off (20061027)
Figure 3: Low frequency regime of Fig.1

Servo on (20061031)

Δf = 0.025Hz
Polarization peak 1: 0.625Hz
Polarization peak 2: 1.25Hz
Polarization peak 3: 2.5Hz

Servo off (20061027)

Δf = 0.025Hz
Figure 4: Bode plot

$G = 20 \log_{10}(A_{on}/A_{off})$

$A_{on}$: amplitude in servo on
$A_{off}$: amplitude in servo off
$G$: Gain
Data Set 2
Figure 5: Other date (meanings are same as Fig.1)

$\Delta f = 0.5\text{Hz}$

CTM-X (black) and CTM-Y (red) Filename=20071215 (Servo on)

CTM-X (black) and CTM-Y (red) Filename=20071215 (Servo off)
Figure 6: Other date (meanings are same as Fig. 2)

$\Delta f = 0.5 \text{Hz}$
Figure 7: Bode plot

\[ G = 20 \log_{10}(A_{\text{on}}/A_{\text{off}}) \]

- \( A_{\text{on}} \): amplitude in servo on
- \( A_{\text{off}} \): amplitude in servo off
- \( G \): Gain
Data Set 3
Figure 8: Other date (meanings are same as Fig.1)
Figure 9: Other date (meanings are same as Fig. 1)
Figure 10: (Bode plot)

\[ G = 20 \log_{10}(A_{on}/A_{off}) \]

- \( A_{on} \): amplitude in servo on
- \( A_{off} \): amplitude in servo off
- \( G \): Gain