Solar Rotational Modulations of SSI and Correlations with the Variability of TSI

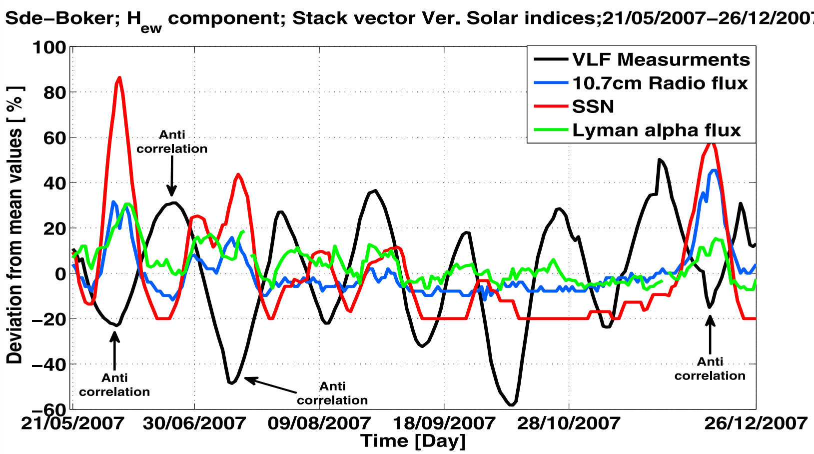
Jae N. Lee[1,2] , Robert F. Cahalan[2,3], and Dong L. Wu[2]

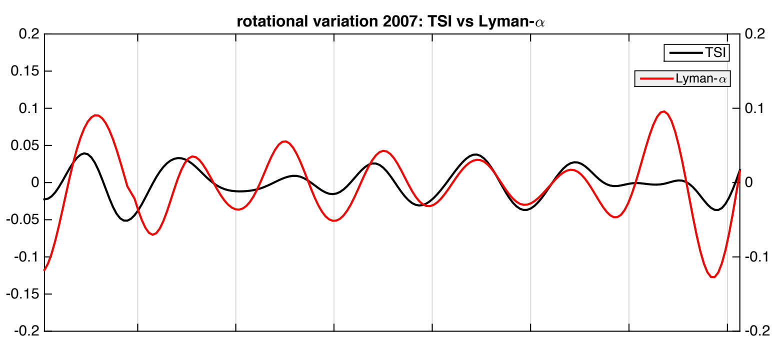
1. Joint Center for Earth Systems Tech., University of Maryland, Baltimore County, MD
2. NASA Goddard Space Flight Center, Greenbelt, MD
3. Applied Physics Lab/Johns Hopkins University, Laurel, MD

1. TSI (TIM, ACRIM III, VIRGO)
2. SSI (SIM V19, SOLSTICE, TIMED/SEE, SATIRE-S)

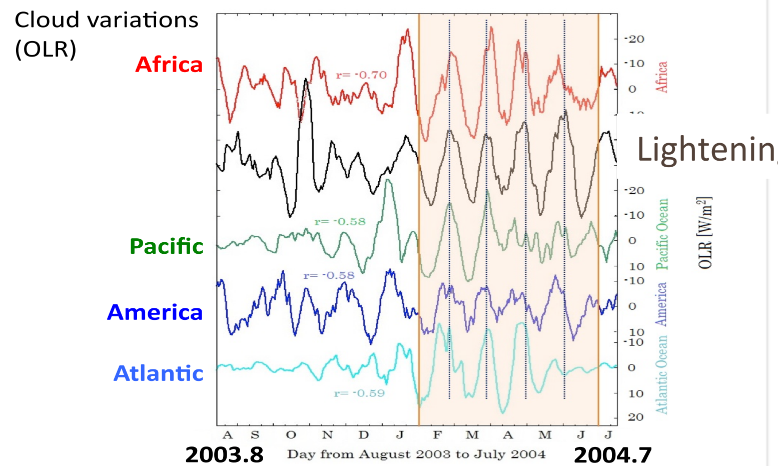
Sun-Climate connection in solar rotational time scale

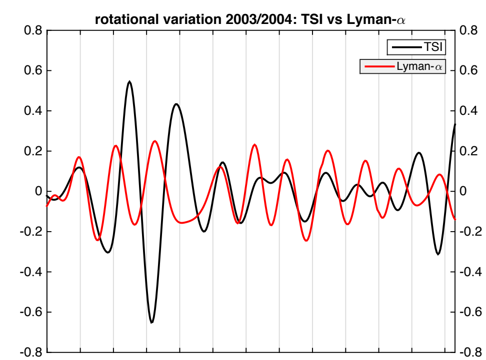
Reuveni and Price (2009)





Takahashi et al. (2014, SORCE meeting presentation)





- VLF lightening signal correlates with solar activity only when the solar rotational signals are large.
- There are 27-day like signals in lightening activity, but not always correlated with solar rotational signals.

TSI and SSI

- SSI is a distribution of TSI, SSI variation is wavelength dependent, and also time scale dependent. Solar spectrum originates at different levels of the solar atmosphere.
- With current satellite observations, more than 100 solar rotational cycles of 27-day variation are covered (2003 – Aug. 2013).
- Distinct solar rotational modulations of SSI at each wavelength can be identified in terms of amplitude and phase.
- The phase of the rotational mode obtained from SSI is compared with that of TSI.

Statistical analysis : EEMD

(Ensemble Empirical Mode Decomposition)

[Huang et al., 1998; Ruzmaikin et al., 2007; Barnhart and Eichinger, 2011]

$$I = \bar{I} + I_{11} + I_R + I^* + e \qquad Eq.(1)$$

I : Total Solar Irradiance

$\bar{I}$ *: Mean of TSI*

I_{11} *: 11 years solar cycle variation* ⟷ Low frequency variation

I_R : $I_{13.5} + I_{27} + I_{54}$ *: 13.5, 27, and 54 day solar rotational variations*

I^* *: Short-term variation (solar noise)*

e: Instrument error

} High frequency variation

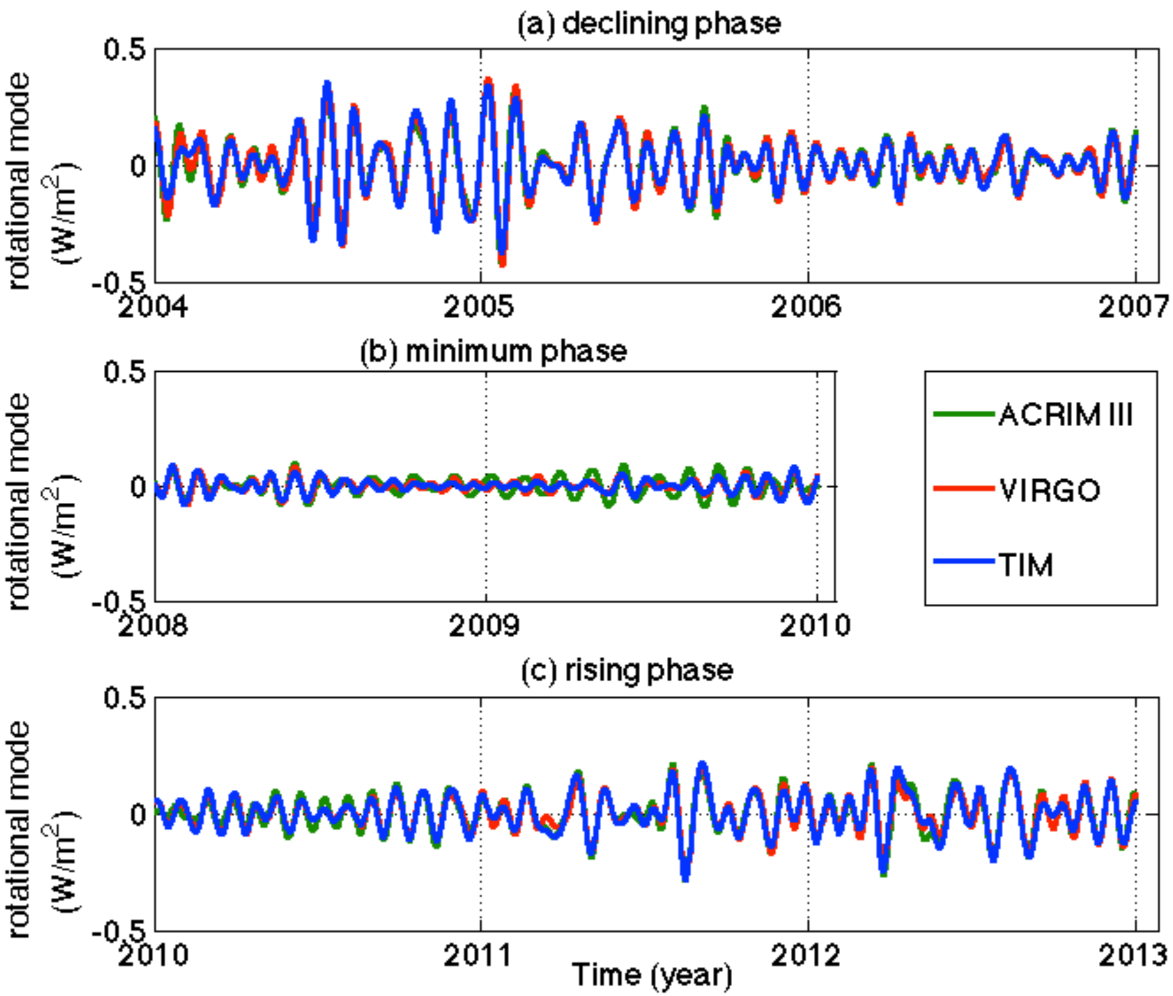
$$X(t) = \sum_j A_j e^{i\omega_j t} \qquad Eq.(2)$$

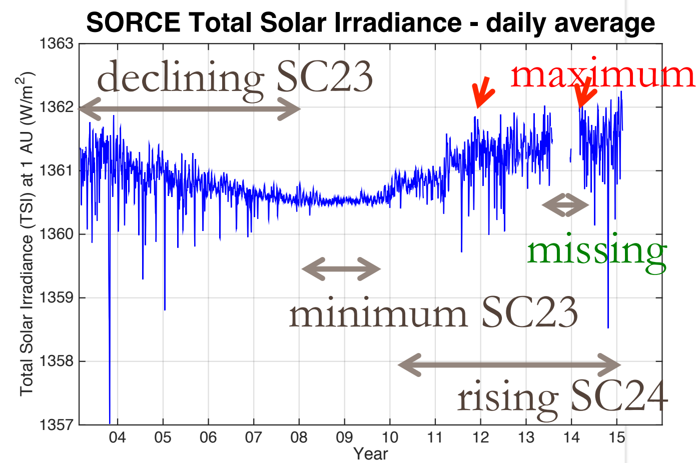
Fourier Transform

$$X(t) = \sum_j A_j(t) e^{i\int \omega_j(t)dt} \qquad Eq.(3)$$

EEMD
Hilbert-Huang Transform with
time variable amplitudes and phases

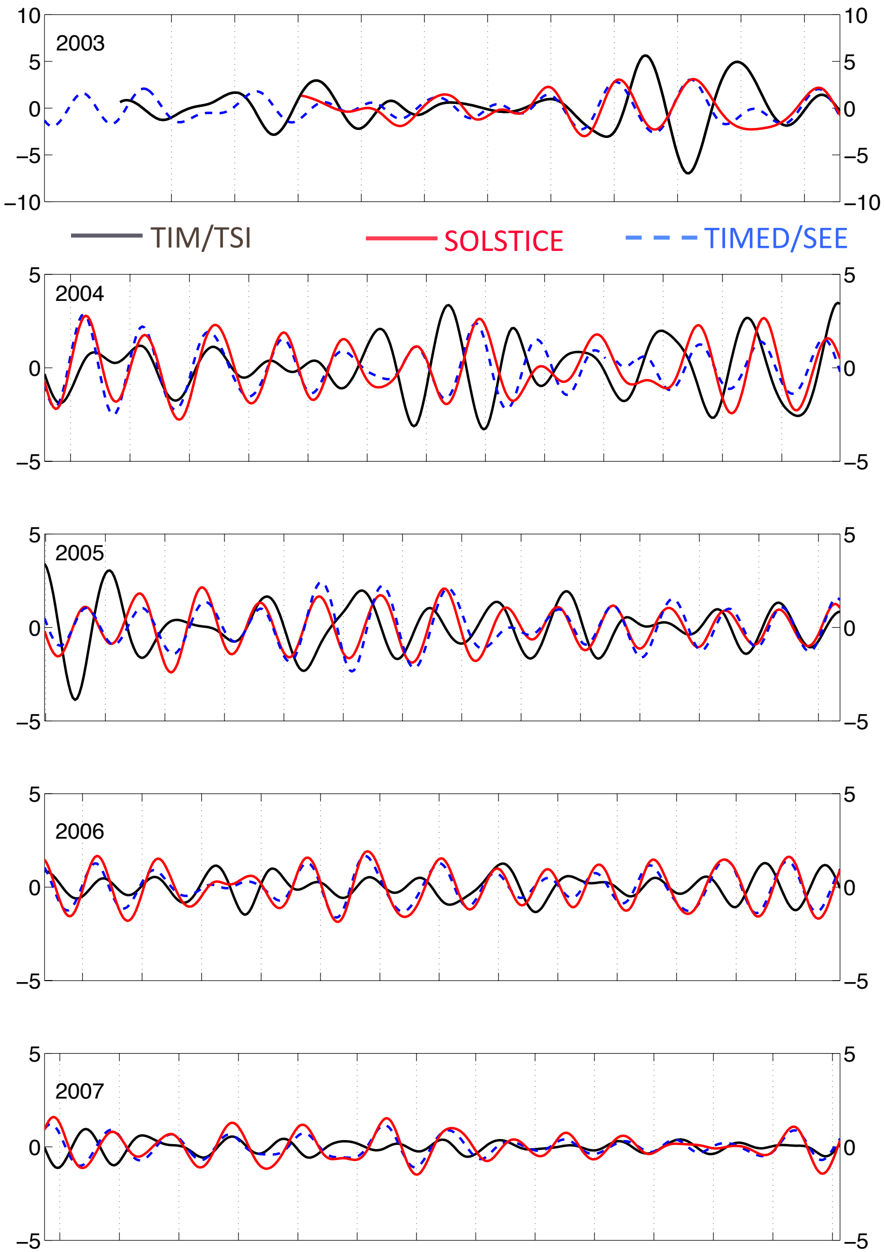
The 27-Day Rotational Variations in TSI Observations: from SORCE/TIM, ACRIMSAT/ACRIM III, and SOHO/VIRGO [Lee et al., 2015]





- The rotational signals are well captured with three independent space-borne TSI measurements.
- They agree well with each other, with large amplitudes in declining and rising phases, but with small amplitudes in minimum phase.
- How about SSI?

Rotational Variation : TSI vs Lyman-α (121 nm)



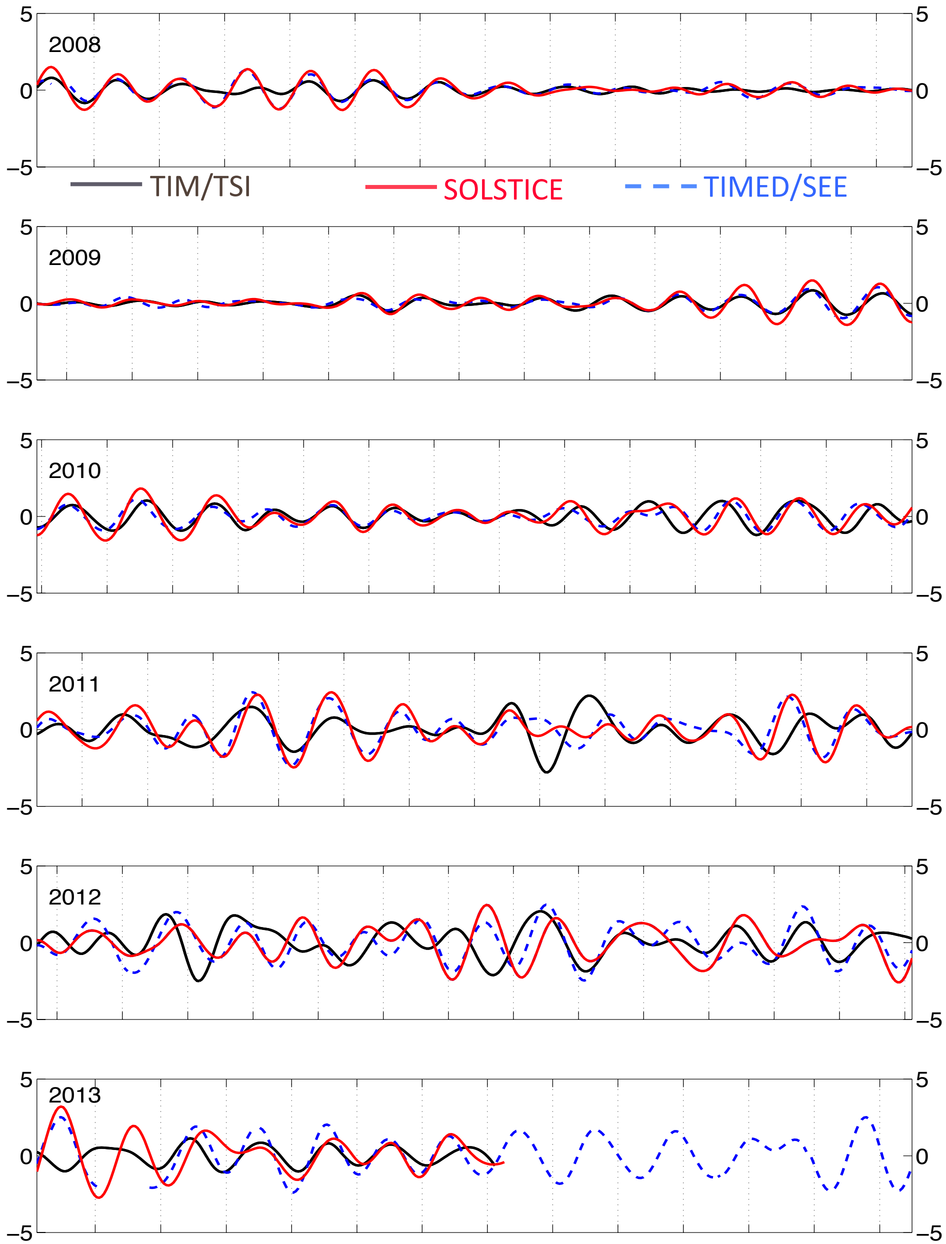
A few examples : How rotational variations of SSI are related with that of TSI?

- Standardized amplitudes are estimated by removing the mean and by dividing with σ.

$$A_{TSI}(t) = \frac{I_{TSI}(t) - \overline{I_{TSI}}}{\sigma(I_{TSI})} , \quad A_{UV}(t) = \frac{I_{UV}(t) - \overline{I_{UV}}}{\sigma(I_{UV})}$$

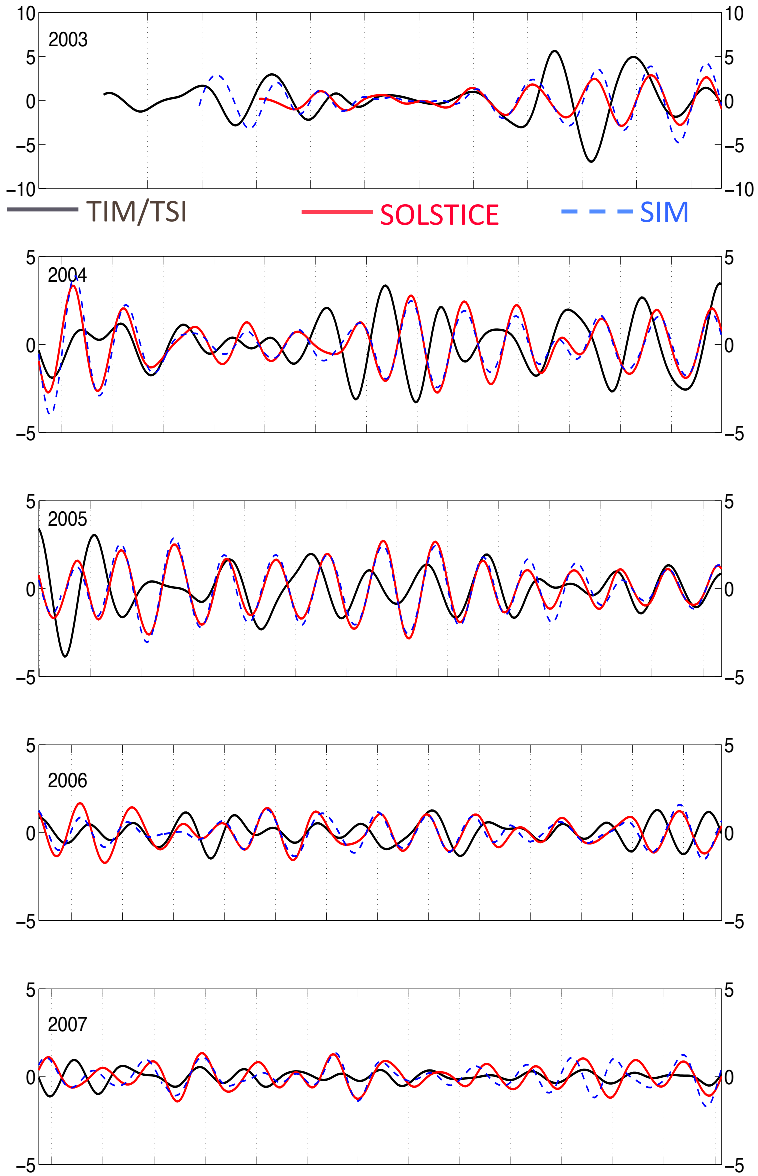
- The modes from two observations of Lyman-α line (SORCE/SOLSTICE and TIMED/SEE) agree well in amplitudes and phases.
- The modes of Lyman-α line are not always in phase with TIM/TSI modes.
- TSI variations are affected by solar proton event (SPE), but UV variations are not.

Rotational Variation : TSI vs Lyman-α (121 nm)



- Rotational variations of TSI and Lyman-α are often out-phase during high solar activity period, but are in-phase during solar minimum (2008-2010).

Rotational Variation : TSI vs MUV (240 nm)

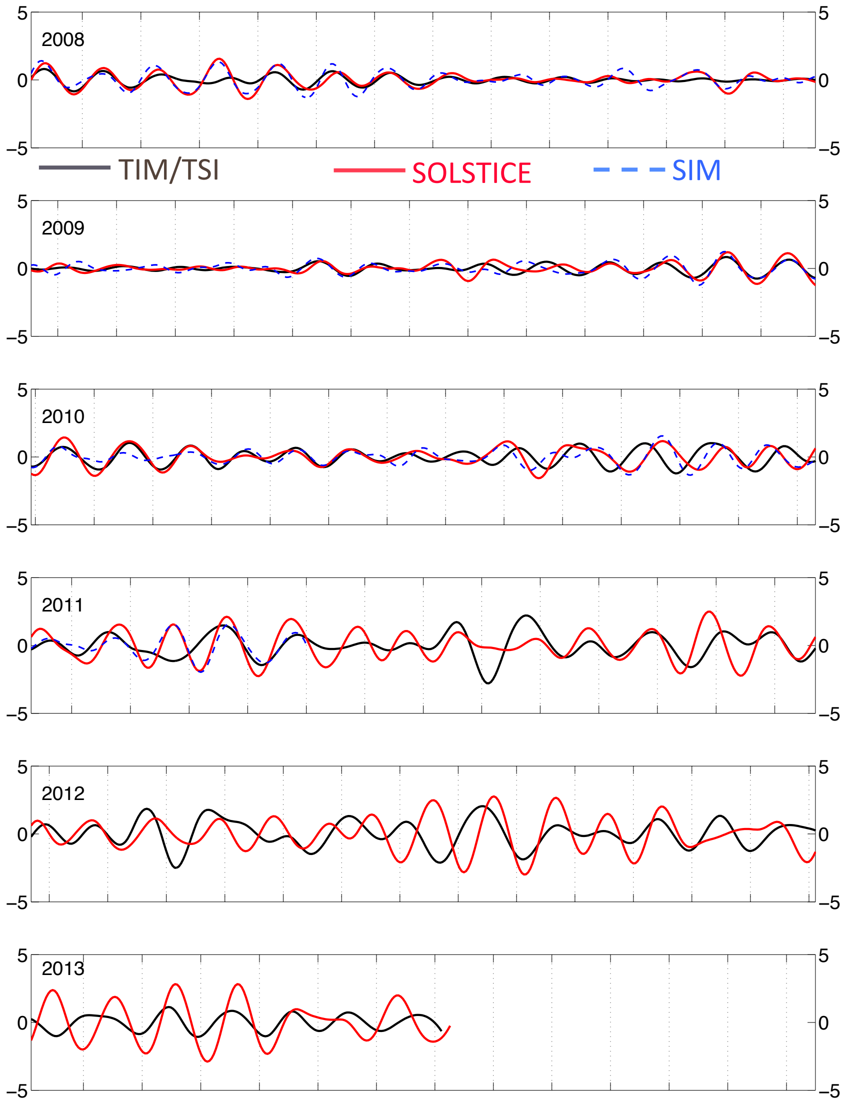


Similar but TSI with MUV (240nm)

- They are often out-phase during high solar activity period.

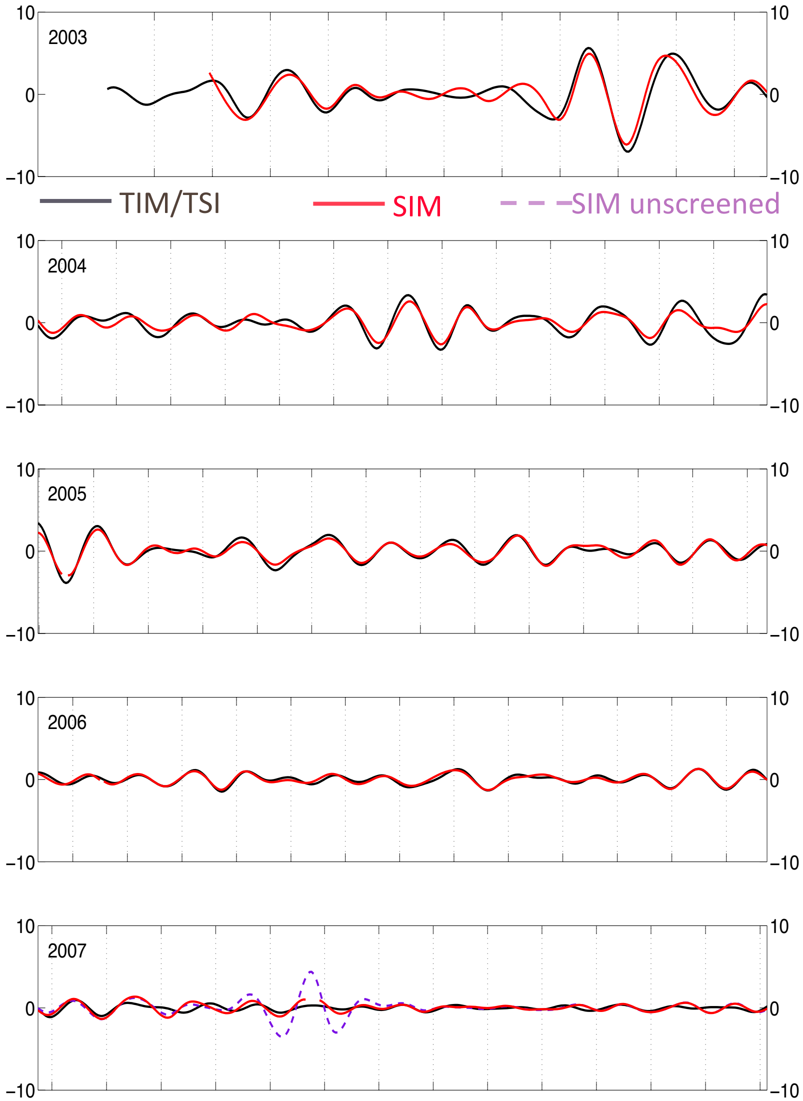
- Modes from SIM and SOLSTICE match well.

Rotational Variation : TSI vs MUV (240 nm)



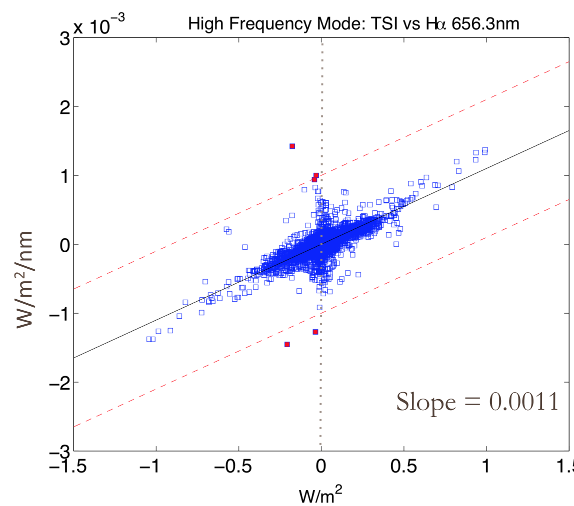
- TSI and MUV are in phase during minimum phase, but often out-phase during solar activity rising period.

Rotational Variation : TSI vs H-α (656 nm)

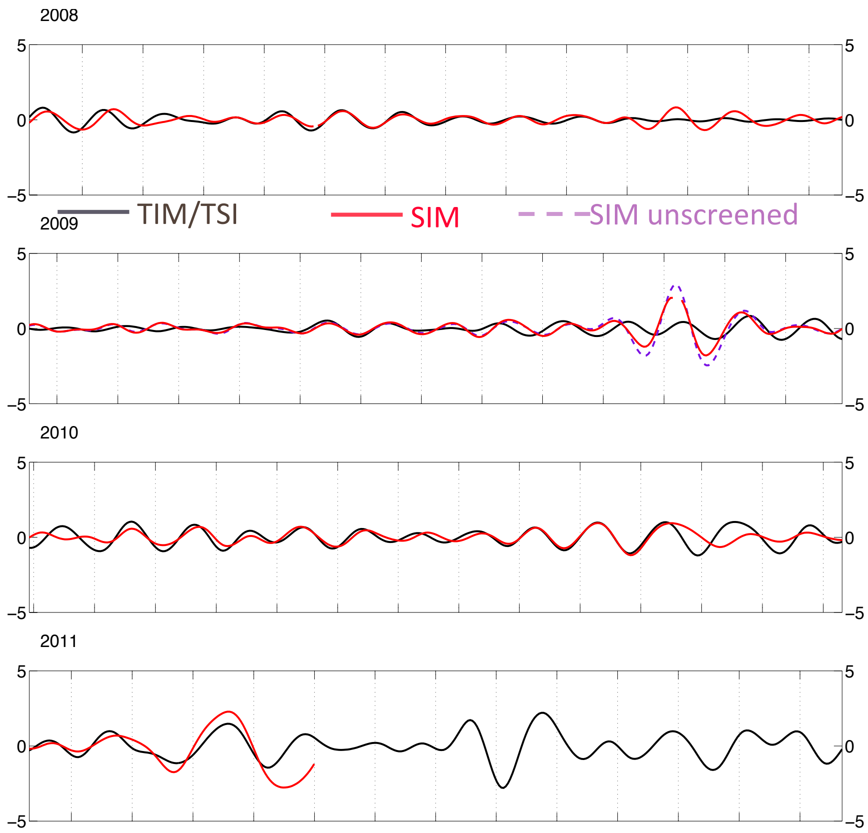


- TSI and VIS are in-phase during whole analysis period (2003 – 2011).

- Only 5 outliers from SIM are excluded for the EEMD analysis to remove the outstanding cycles appeared in purple dotted curve.
- Outliers from SIM are chosen from high frequency mode comparison with TSI.



Rotational Variation : TSI vs. H-α (656 nm)

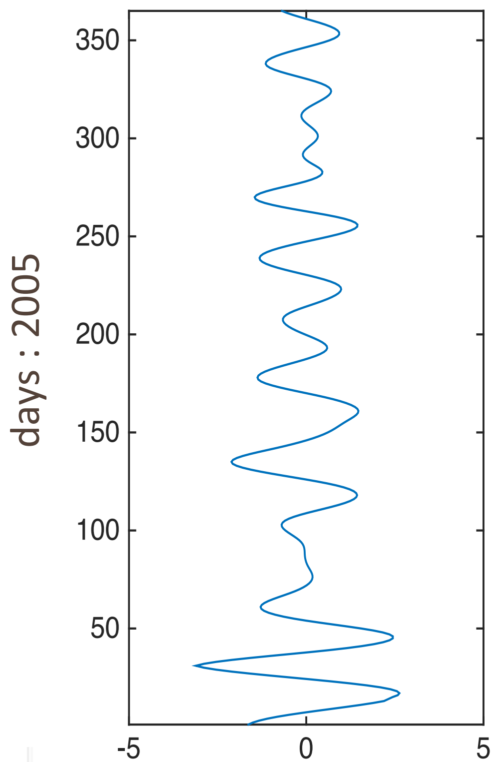


TSI and SIM H-α (656 nm)

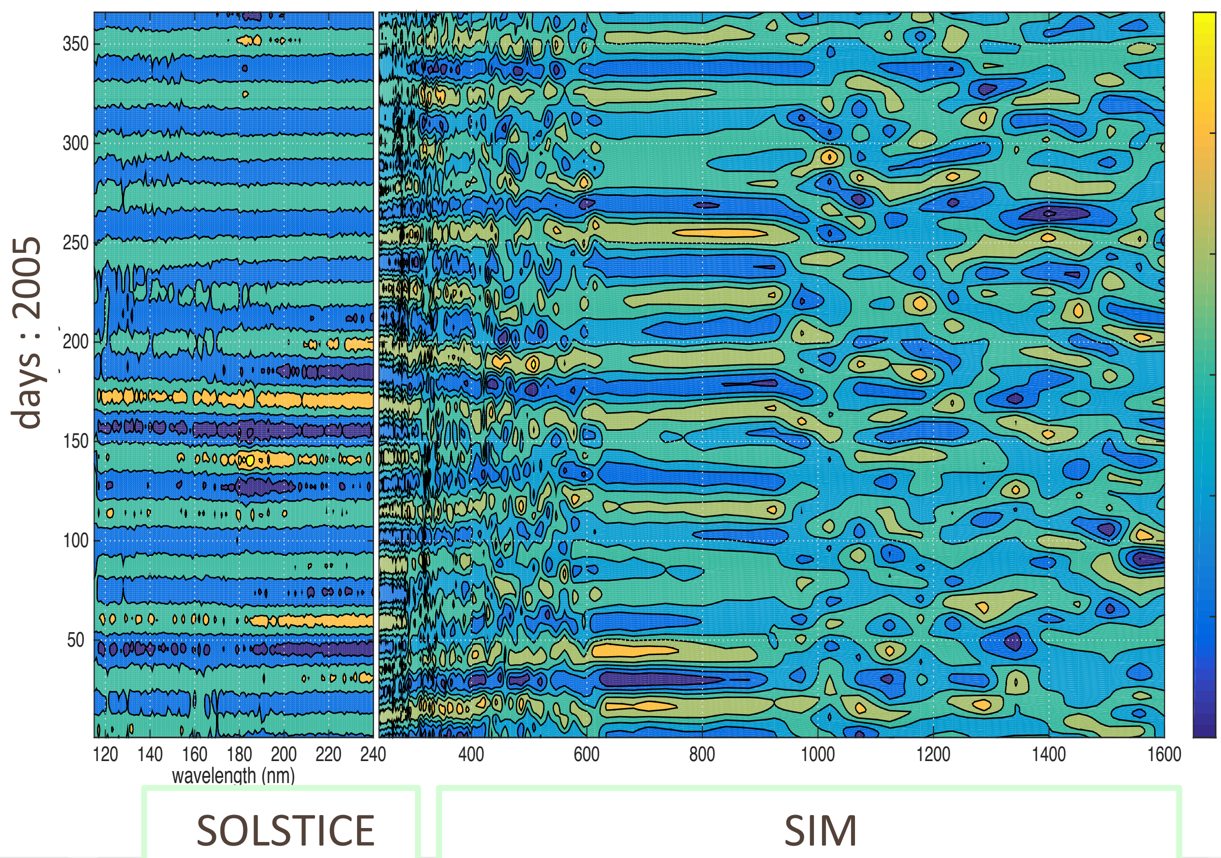
Phase of the solar rotational modes : 2005

- Rotational variations are well defined in UV and 600- 900 nm, but not at photospheric wavelength (250 – 600 nm) and IR above 900 nm.

mode of TSI: 2005

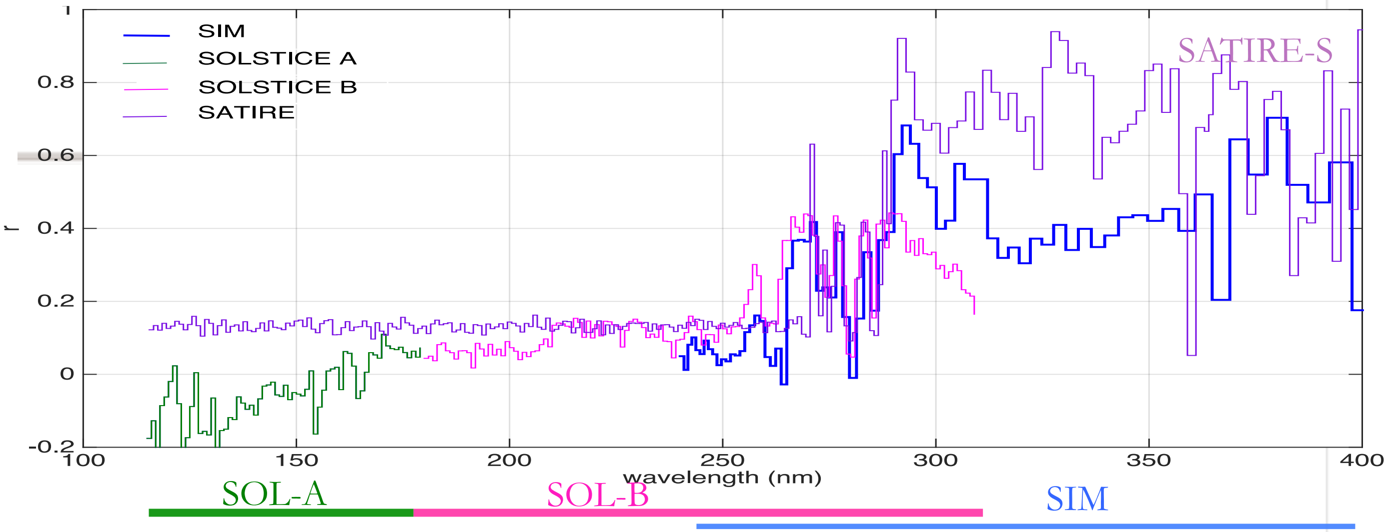


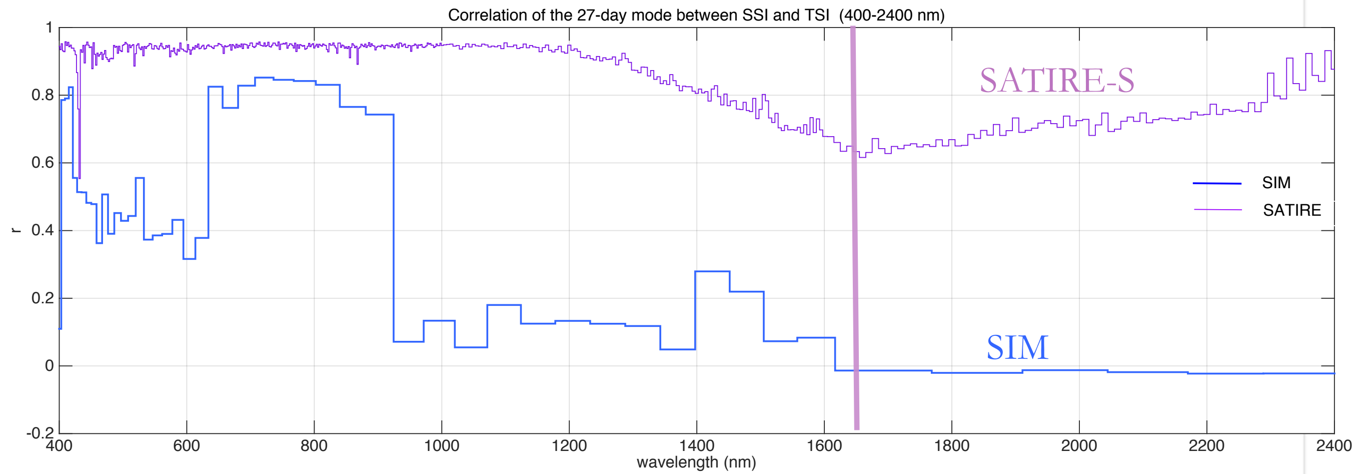
mode of SSI: 2005



Linear correlations of the 27-day mode between TSI and SSI

- Correlations begin to grow at 250 nm, correlations from SOLSTICE, SIM and SATIRE track each other.
- Correlations from SIM is >0.8 in 600 – 900 nm.
- Correlations from SATIRE are nearly 1 above 400 nm, but shift at opaque minimum at 1650 nm.





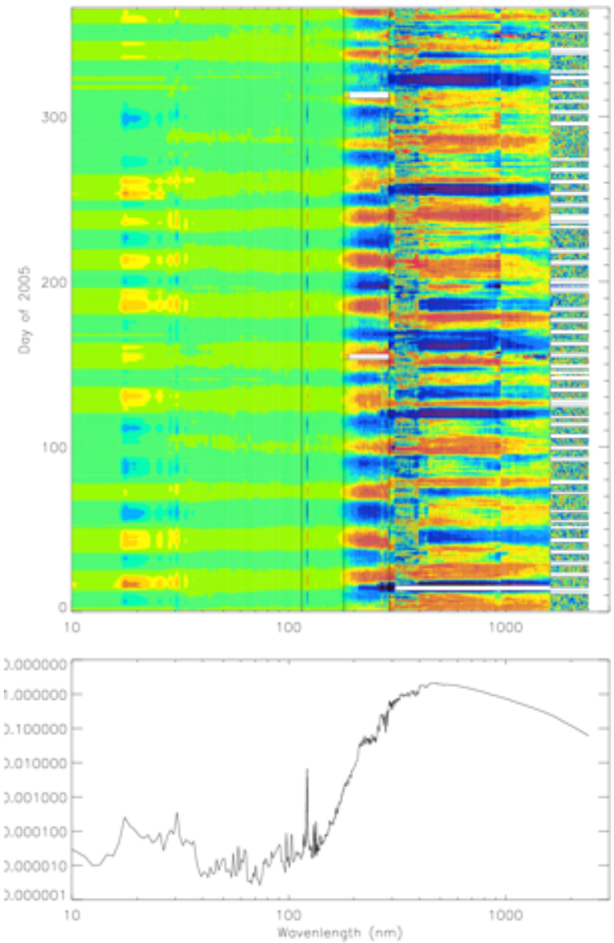
Summary

- Solar rotational modulations of spectral irradiance are wavelength dependent.
- Rotational variations of VIS and NIR (~600-900 nm) are in-phase with that of TSI, but variations of FUV and MUV are not always in-phase.
- Close agreement of the rotational variations from SIM and SOLSTICE is encouraging. We can address rotational variations from SORCE SSI measurements with high confidence.
- Rotational variations from SATIRE-S matches with observed SSI modes below 280 nm, and exactly matches with TSI mode above 400nm.

Acknowledgment

- SORCE Team
- TIMED and SATIRE Teams
- Tom Woods, Jerry Harder, and Marty Snow

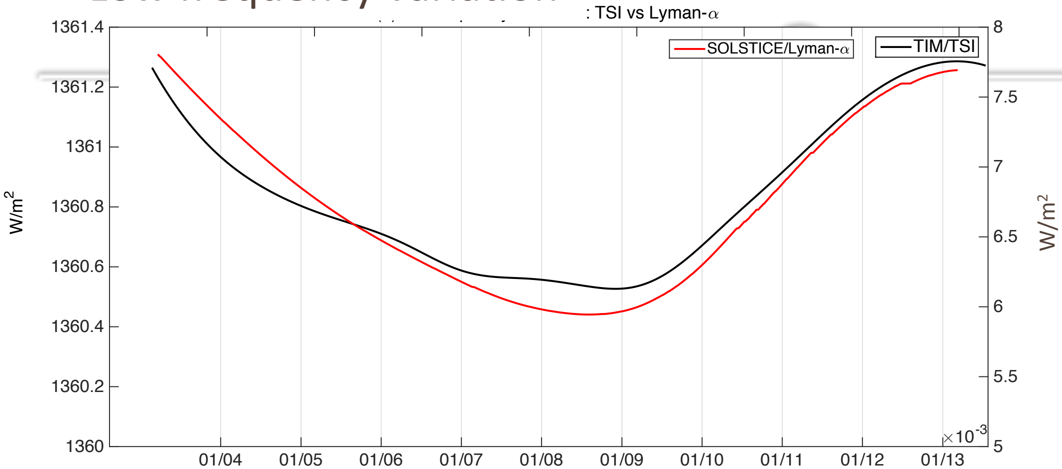
Back ups



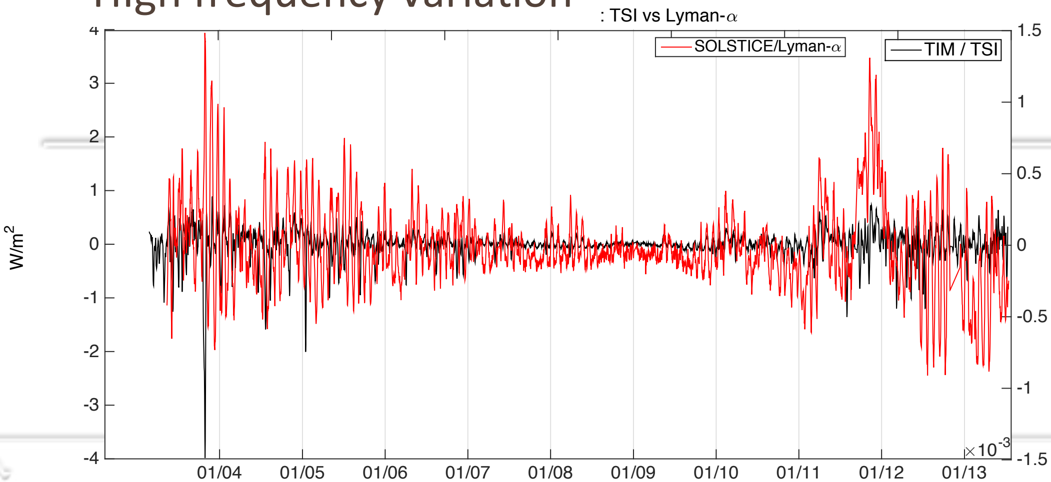
Day of 2005
300
200
100
0
10
100
1000
0.000001
0.000010
0.000100
0.001000
0.010000
0.100000
1.000000
Wavelength (nm)

Low frequency and High frequency variations of TSI and Lyman-α

Low frequency variation

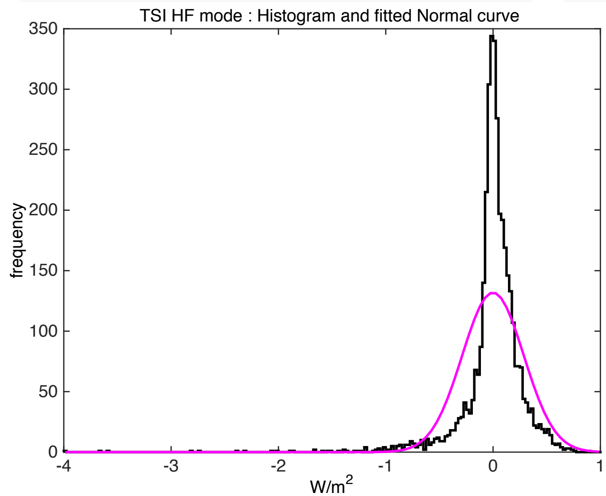


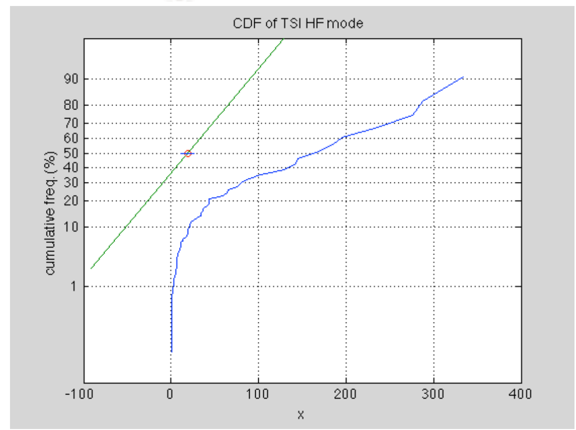
HIgh frequency variation



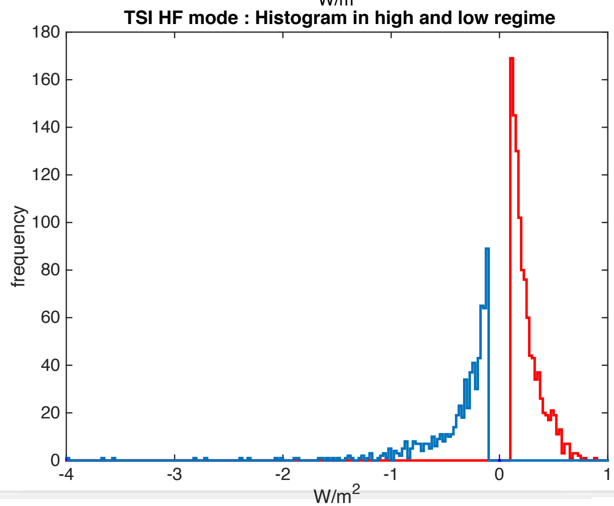
- The phase of low and high frequency variations of TSI and Lyman-α line are compared.
- Amplitudes of high frequency variation
- Low frequency variations are in-phase with each other.
- High frequency variations?

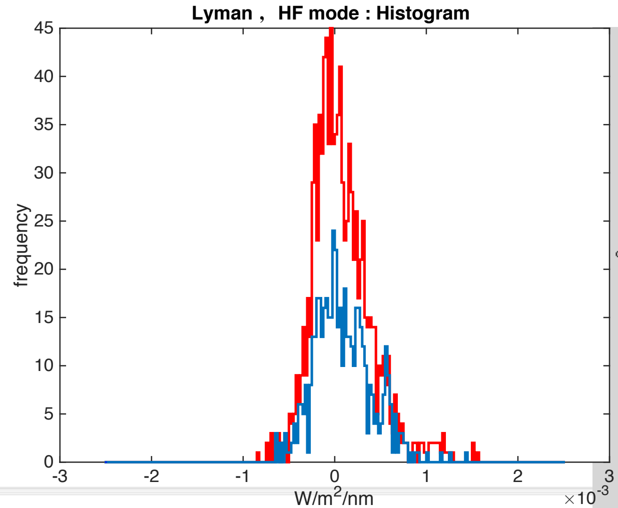
Distribution of low and high frequency modes

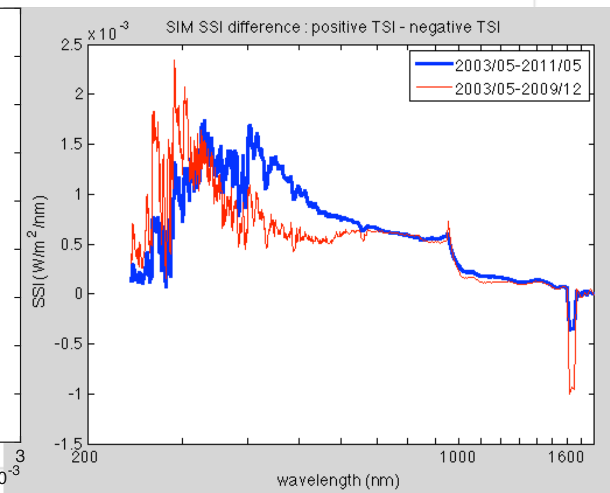




- TSI HF mode is not normally distributed.
- SIM SSI difference between high and low TSI regime has a dip at 1600nm.





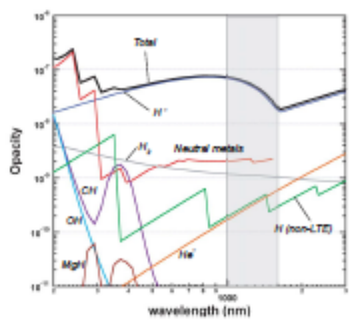


Eric Richard's TSI vs SSI

$$I(\lambda) = I_0 \exp(-Ox) \approx I_0 (1 - Ox)$$

1. Relation between irradiance I and Opacity

→ here O is opacity and x is distance times density. Note O depends on the wave length lambda

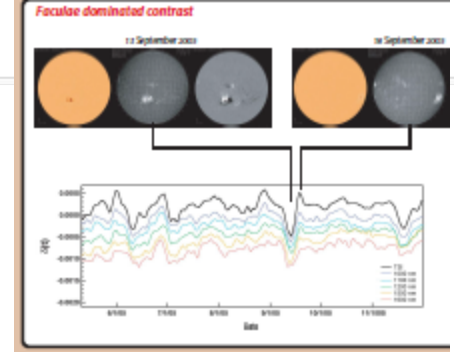


2. Assume there are two main source of absorption such as O1: H- and O2:H2

→ Then

$$I(\lambda) = I_0 (1 - O_1 x_1 - O_2 x_2)$$

3. Let us see if the following fig makes sense



→ the y axis is defined as

$$d(\lambda) = \frac{I - I_{ref}}{I_{ref}} = \frac{I_0\left(1 - O_1 x_1 - O_2 x_2\right) - I_0\left(1 - O_1 x_1 - O_2 x_2\right)_{ref}}{I_0\left(1 - O_1 x_1 - O_2 x_2\right)_{ref}}$$

$$= \frac{O_1\left(x_{1,ref} - x_1\right) + O_2\left(x_{2,ref} - x_2\right)}{\left(1 - O_1 x_1 - O_2 x_2\right)_{ref}}$$

4. We can compare two wave length 1000 and 1600.

$$d(1000)=\frac{O_1(1000)\left(x_{1,ref}-x_1\right)+O_2(1000)\left(x_{2,ref}-x_2\right)}{\left(1-O_1(1000)x_1-O_2(1000)x_2\right)_{ref}}$$

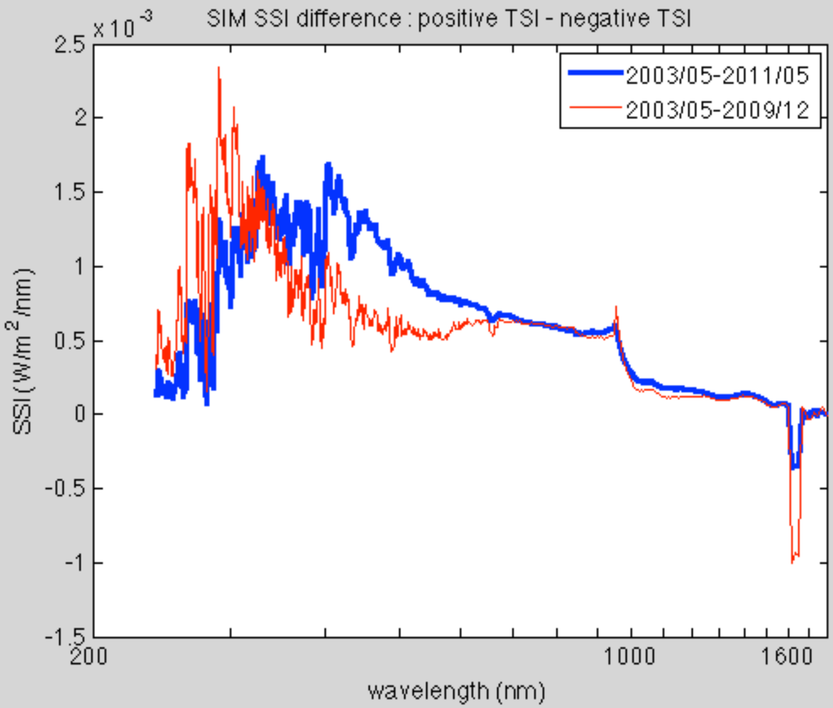
$$d(1600)=\frac{O_1(1600)\left(x_{1,ref}-x_1\right)+O_2(1600)\left(x_{2,ref}-x_2\right)}{\left(1-O_1(1600)x_1-O_2(1600)x_2\right)_{ref}}$$

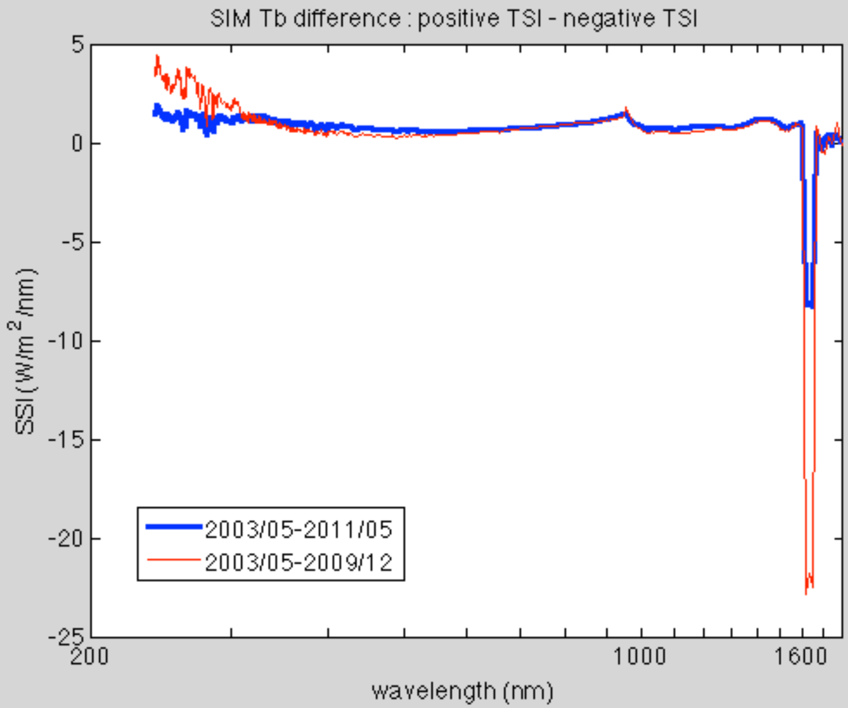
5. Note in general lager fluctuation for lambda 1000 than 16000 because

$$\frac{1}{\left(1-O_1(1000)x_1-O_2(1000)x_2\right)_{ref}}>\frac{1}{\left(1-O_1(1600)x_1-O_2(1600)x_2\right)_{ref}}$$

6. Also, depending on relative abundance (density) of H- and H2, that is x1 and x2, the sign of d(1000) and d(1600) can be different. That is while one grows , the other could decrease.

SSI composite: TSI(high) – TSI(low)





SSI composite: TSI(asc) – TSI(des)