Long-term variability of the high speed solar wind

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Outline

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- Data and Methods
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  - HSSs Intensity (Importance) during SCs 20 – 23
- Lomb - Scargle Method
  - Periodicities
- Fast Fourier Transform
  - Phase shift between W and HSSs during 11-yr SCs

Solar Wind (SW)

<u>There is much about the solar wind that we do not understand</u> because:

• the origin of the solar wind is complex;

• the region of solar wind acceleration has not been probed with in situ investigations.

In contrast, <u>we know much about the solar wind at the orbit of the Earth and of some space missions</u> (<u>from the mid 1970s on, e.g. Skylab, Helios, Voyager and Ulysses</u>) :

• It flows with a speed of about 350 km/s and a density of 5 cm^{-3};

• It carries a magnetic field of about 5 nT that lies near the ecliptic plane in an Archimedean spiral pattern;

• It is highly variable.

<u>A real steps forward occurred in the mid 1990s when the Yohkoh, SOHO, WIND, ACE, and TRACE spacecrafts went into operation</u>

History

- **March 1716** – the first interpretation of an 'aurora' based on exact sciences → as a terrestrial phenomenon which involved geomagnetism (magnetic thunderstorms);
- **1859 – solar flare in white light** → geomagnetic storm (GSs);
  - **Solar M regions** → recurrent geomagnetic storms (27 days);
- **Solar wind (Parker) 1956** → space era 1957→ terrestrial magnetosphere, Van Allen radiation belts, ...;
- **May 1973 – Skylab** (corona in X-ray and white light) → **Coronal Holes** (***recurrent GSs***) and **Coronal Mass Ejections** (***major GSs***)
- **Heliosphere – planetary magnetospheres**

SW Classification:
- General
- Complex

Average solar wind parameters at 1 AU, for the time around solar activity minimum, compiled by Schwenn (1990).

	Low speed wind (LSW)	Fast wind (HSS)
Flow speed v_p	250 – 400 km s^{-1}	400 – 800 km s^{-1}
Proton density n_p	10.7 cm^{-3}	3.0 cm^{-3}
Proton flux density $n_p\ v_p$	3.7×10^8 cm^{-2} s^{-1}	2.0×10^8 cm^{-2} s^{-1}
Proton temperature T_p	3.4×10^4 K	2.3×10^5 K
Electron temperature T_e	1.3×10^5 K	1×10^5 K
Momentum flux density	2.12×10^8 dyne cm^{-2}	2.26×10^8 dyne cm^{-2}
Total energy flux density	1.55 erg cm^{-2} s^{-1}	1.43 erg cm^{-2} s^{-1}
Helium content n_p / n_{He}	2.5%, variable	3.6%, stationary

Solar Wind type I (solar minimum)

1. Fast wind in high-speed streams

• High speed	400 - 800 kms^{-1}
• Low density	3 cm^{-3}
• Low particle flux	2×10^{8} cm^{-2} s^{-1}
• Helium content	3.6 %, stationary
• Source	coronal holes
• Signatures	stationary for long times (days – weeks)

2. Low speed wind near activity minimum

• Low speed	250 – 400 km s^{-1}
• High density	10 cm^{-3}
• High particle flux	3.7×10^{8} cm^{-2} s^{-1}
• Helium content	below 2 %, highly variable
• Source	helmet streamers near current sheet
• Signatures	sector boundaries embedded

Solar Wind type II (solar maximum):

3. Low speed wind

Similar characteristics as 2., except for:

• Helium content	highly variable
• Source	related to active regions
• Signatures	shock waves often imbedded

4. Ejecta following interplanetary shocks

• High speed	400 – 2000 kms^{-1}
• Helium content	up to 30%
• Other constituents	often Fe^{l6+} ions; in rare cases He^{+}
• Sign. of magnetic clouds	in about 30% of cases
• Sources	CMEs, erupting prominences, flares

HSS definition

HSS – a large increase in the SW velocity lasting by several days

- Intriligator (1973) – HSS as a stream having a rapidly rising increase in solar wind speed and **a peak velocity ≥ 450 km/s**;

- Bame et al. (1976) and Gosling et al. (1976) define a HSS as an observed variation of solar wind speed characterized by **an increase of at least 150 km/s within a 5-day interval;**

- Broussard et al. (1977) define a HSS as wind period in which the **solar wind speed is ≥ 500 km/s averaged over a day**

Catalogues of HSSs

MAIN SELECTION CRITERIA:

- **SCs. 20; 21; 23: $\Delta V_1 \geq 100$ km/s lasting for two days, where: ΔV_1 – the difference between the smallest 3-hr velocity mean value for a given day (V_0) and the largest 3-hr value the following day (V_1);**
  - **SCs nos. 20 – 21 (1964-1982):**
    - Lindblad, B.A., Lundstedt, H., 1981, Sol. Phys. 74, 197-206; 1983, Sol. Phys. 88, 377-382;
    - Lindblad, B.A., Lundstedt, H., Larsson B., 1989, Sol. Phys. 120, 145-152;
  - **SC no. 23 (1996 – 2008)**
    - Maris, O., Maris G., 2007: www.spacescience.ro/new1/HSS_Catalogue.html; http://www.spaceweather.eu/, in Cap. "Data Catalogs for SW"
- **SC 22: Difference between the maximum daily speed and the mean value between the speeds immediately preceding and following the stream is ≥ 100 km/s lasting for at least two days.**
  - **SC no. 21 – 22 (1982-1995):**
    - Mavromichalaki, H., Vassilaki, A., Marmatsouri, E., 1988, Sol. Phys. 115, 345-365;
    - Mavromichalaki, H., Vassilaki, A., 1998, Sol. Phys. 183, 181-200.

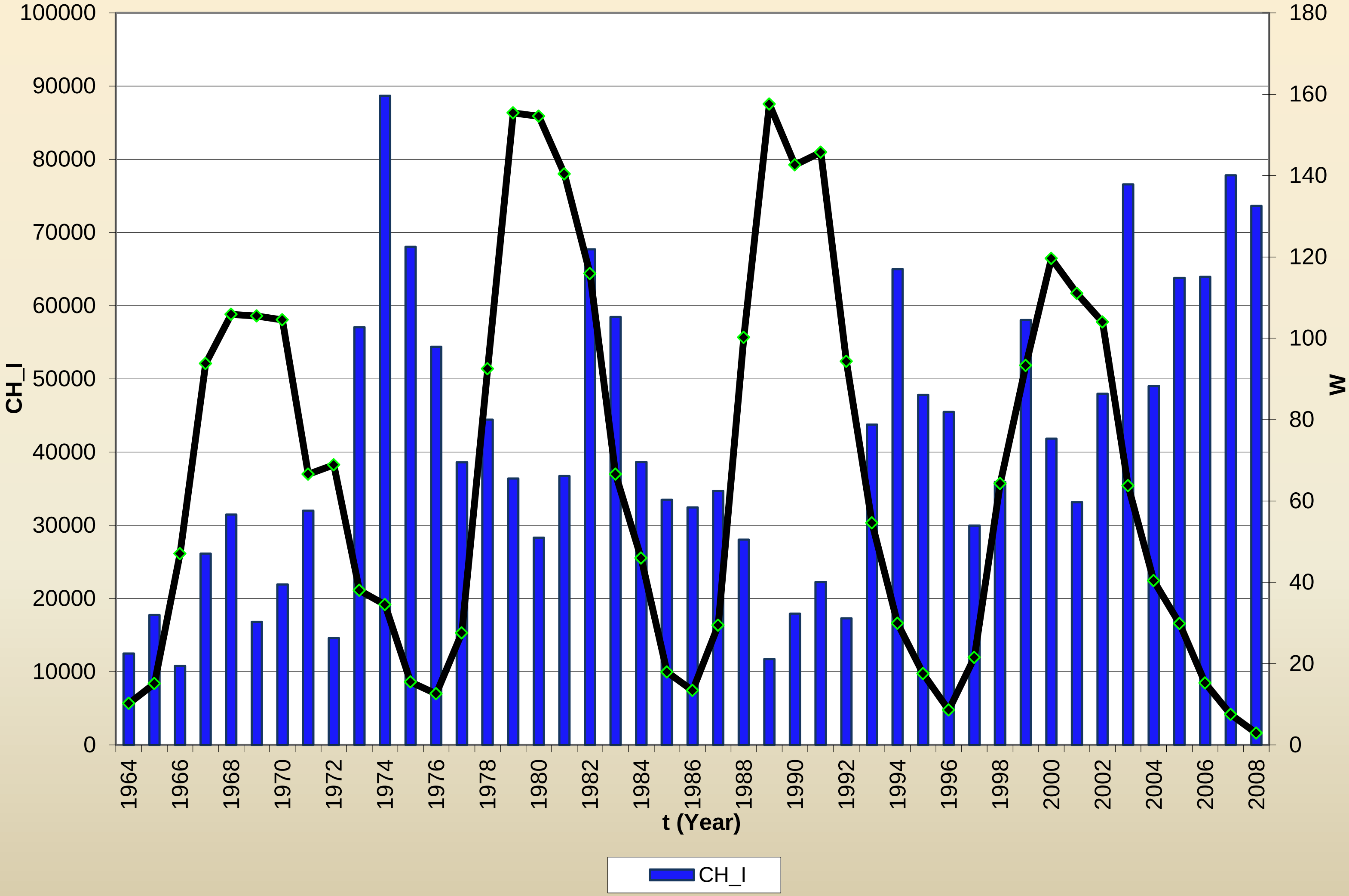
HSS Parameters

- **HSS duration** – ***d*** **(days);**
- **HSS initial velocity – the smallest 3-hr velocity mean value for a given day, V_0 ;**
- **HSS maximum velocity** – **V_{max} (km/sec);**
- **HSS velocity gradient** – **$\Delta V_{max} = V_{max} - V_o$;**
- **HSS importance (or intensity)** – **$I = \Delta V_{max} \times d$**

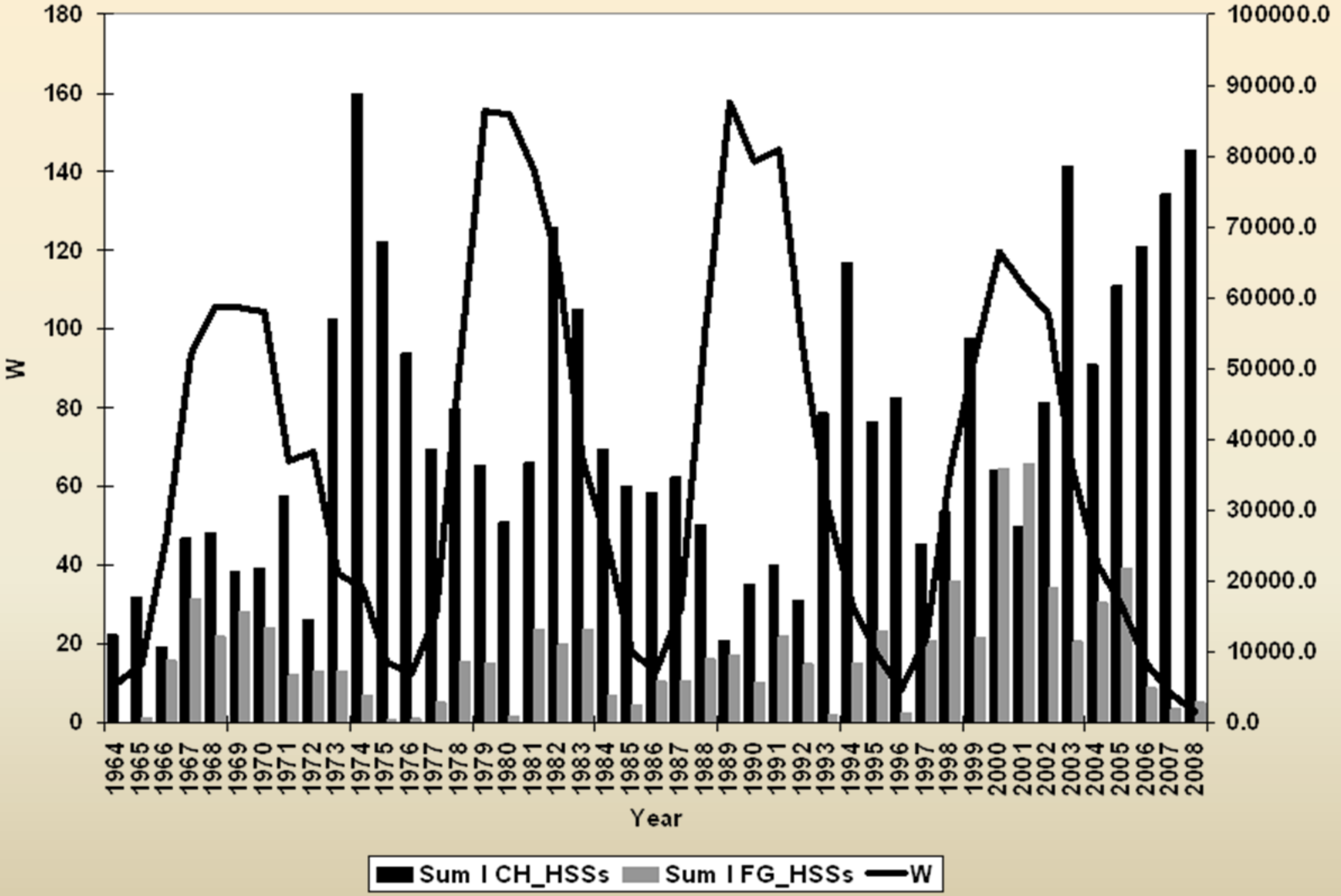
  (ΣI could be used, calculated per BRs, per months, or per years, as well as, the weighted values : $I_p = \sum I / \sum d$)

All these parameters characterize in some manner the energy of the events; the *<u>HSS Importance</u>* is considered to be the best one because it includes the velocity gradient as well as the duration of the event.

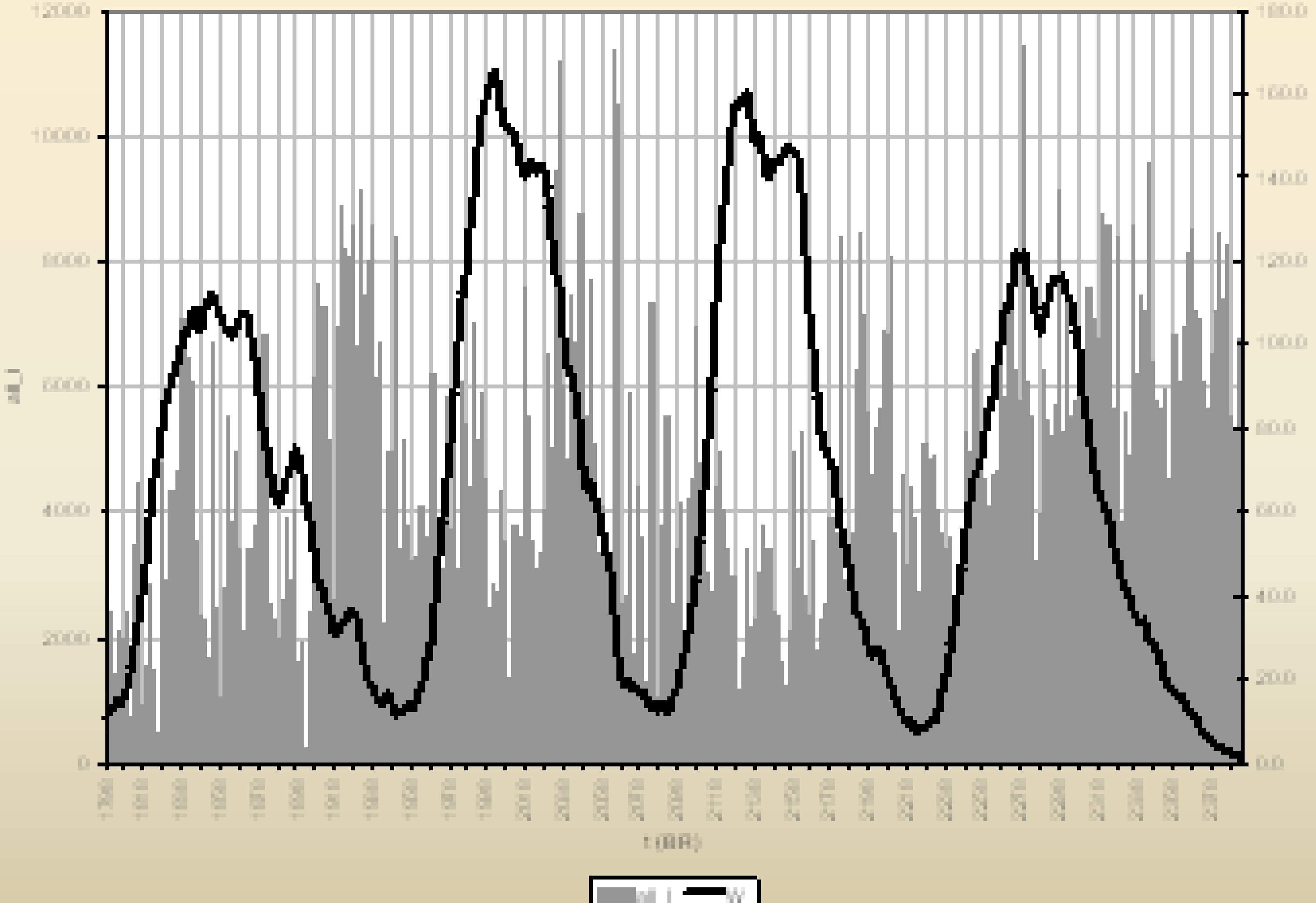
ΣI of CH_HSS (SCs 20 – 23, 1964 -2008)



ΣI of CH_HSS and FG_HSS (SCs 20 – 23, 1964-2008)



ΣI of CH_HSS (per BR)



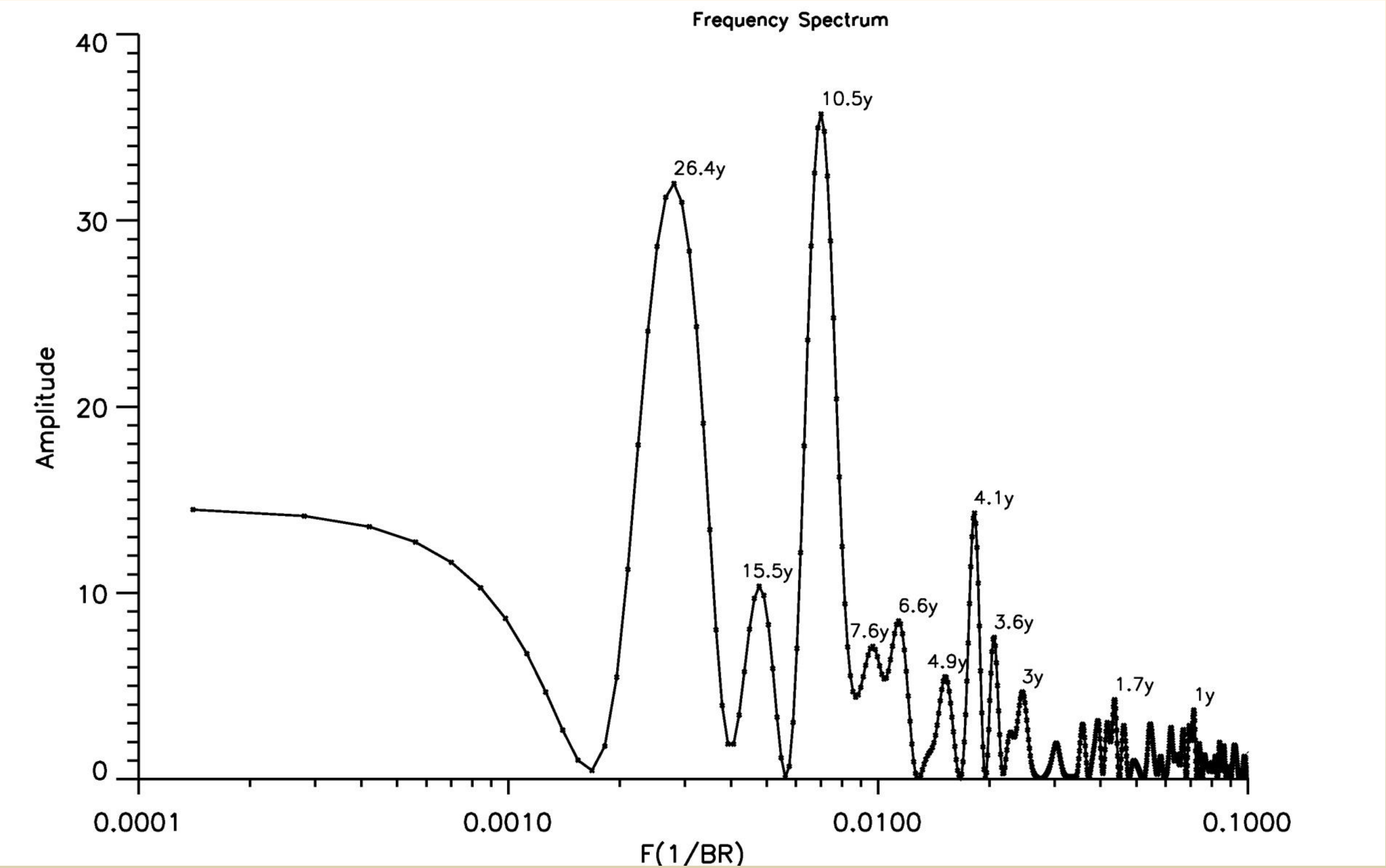
HSS Spectral Analysis:

- Lomb-Scargle method $\Rightarrow$ power spectrum $\Rightarrow$ spectral components
- Fast Fourier Transform (FFT) in LabView graphic programming environment $\Rightarrow$ phase shift between W and HSS importance

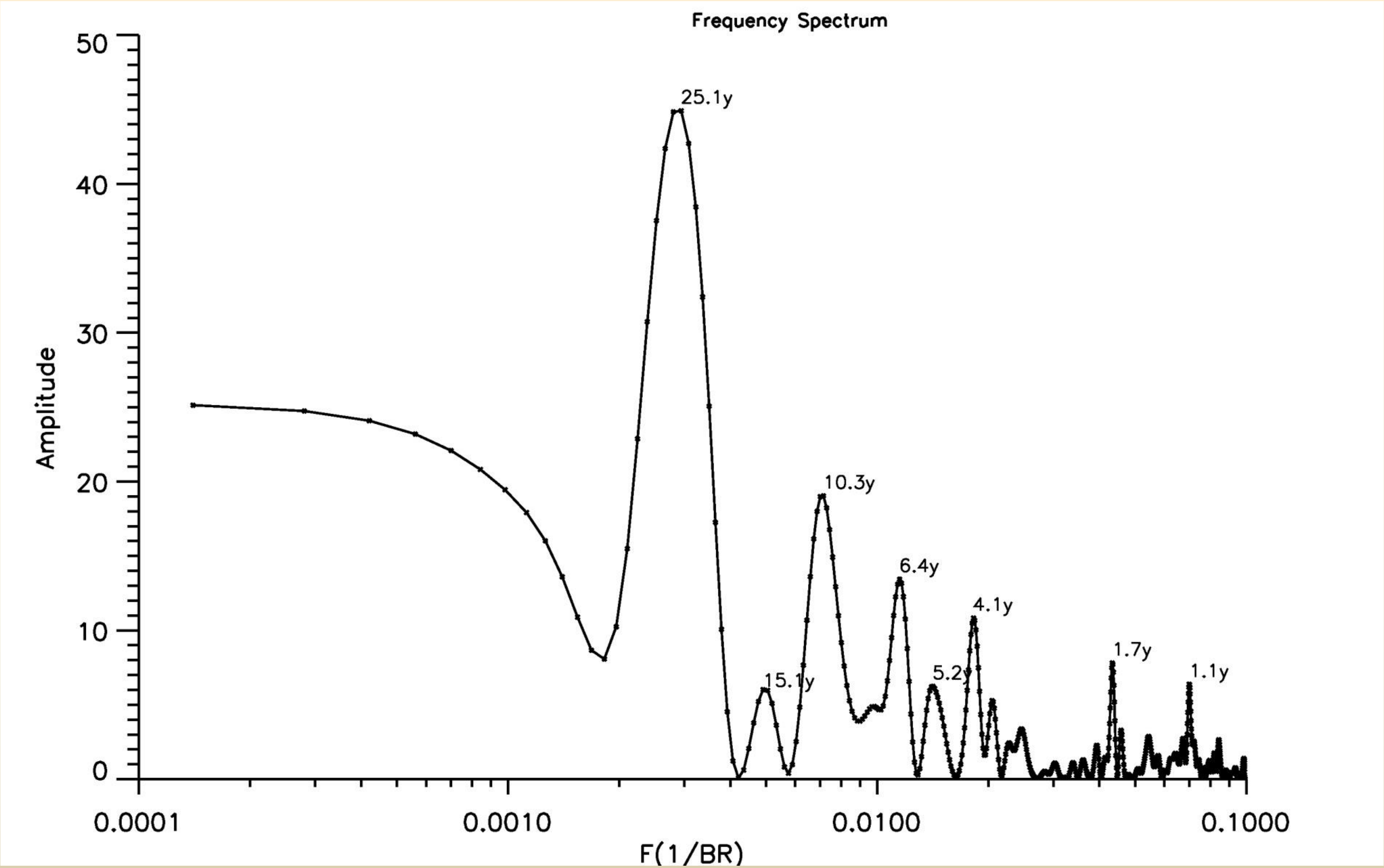
- Time interval: 1964 - 2008

- PARAMETER used:
  - the HSS intensity (importance), ΣI – 27 days resolution (a Bartels Rotation – BR)

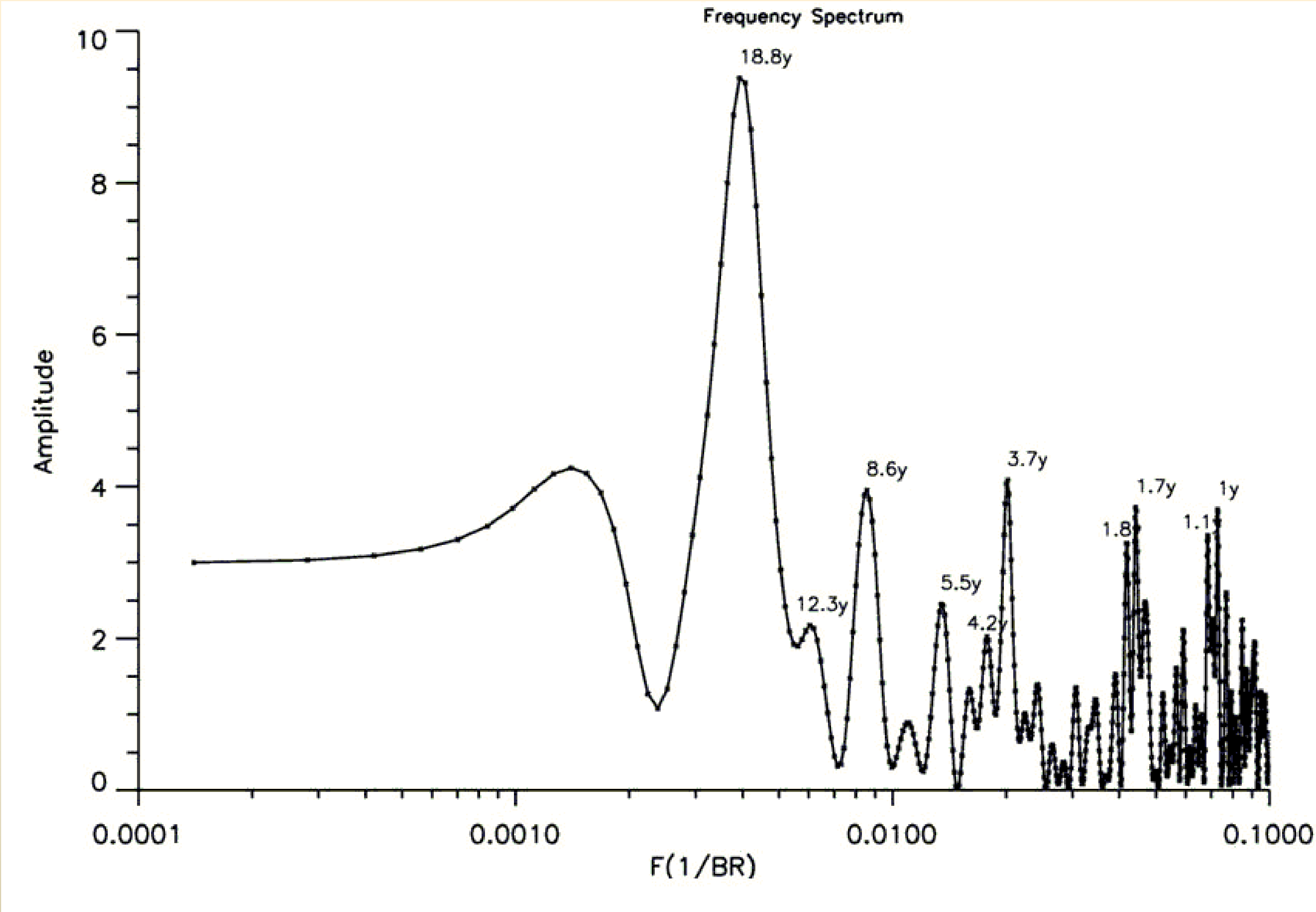
Lomb spectrum of ΣI for the CH_HSSs



Lomb spectrum of ΣI for all_HSSs



Lomb spectrum of the ΣI for FG_HSSs



Periods:

The period $T_{\Sigma I\_HSS}$ of each spectral component found in the Lomb periodogram can be calculate for HSS intensity as:

$$T_{\Sigma I\_HSS,n} = 1/(F_n \times n_B/n_Y)$$

where:

n = Order of spectral component;

F_n = Frequency of the spectral component of n order;

$F_n = n/N$

N = Numbers of spectral series component;

n_B = Number of days per Bartels Rotation (27);

n_Y = Number of days per year (365);

Periods found

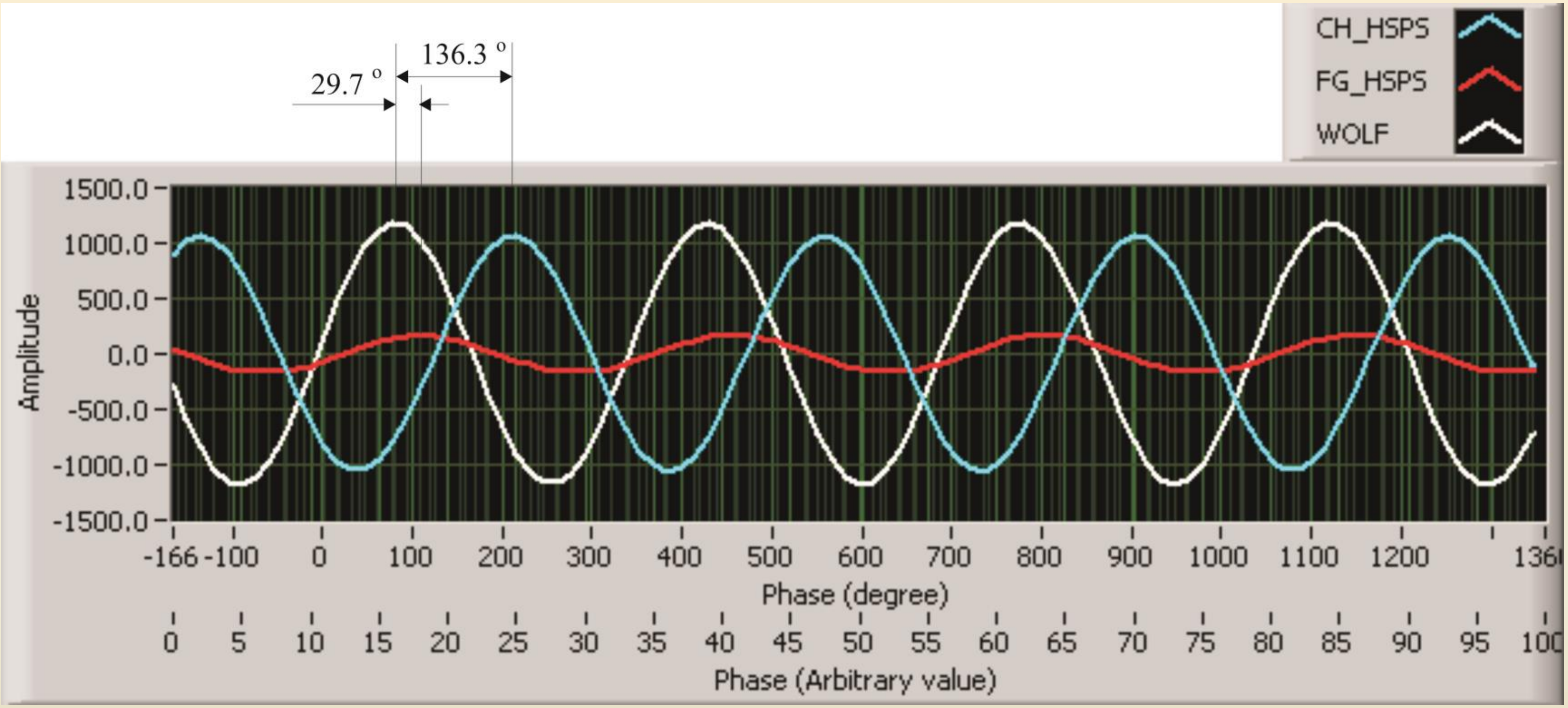
ΣI for CH_HSS	ΣI for all_HSS	ΣI for FG_HSS
26.4	25.1	-
15.5	-	18.8
10.5	10.3	8.6
6.6	6.4	5.5
4.1	4.1	4.2
3.6	-	3.7
3.0	-	0
1.7	1.7	1.7
1.1	1.1	1.0

Our results for solar wind are similar to those obtained by other authors:

- **Kuznetzova, T. V., 2007: 10.8 y, 3.73 y, 1.55 y, 1.3y**
- **Verma, V. K., 2003 (?): 7 y, 2.9 y, 2.4 y, 7 d**
- **Rangarajan, G. K., 1999: 9 y, 3.5 y, 1.33 y**
- **Prabhakaran Nayar S.R., 2002: 10.6 y, 9.6 y, 5.5 y, 1.3 y**

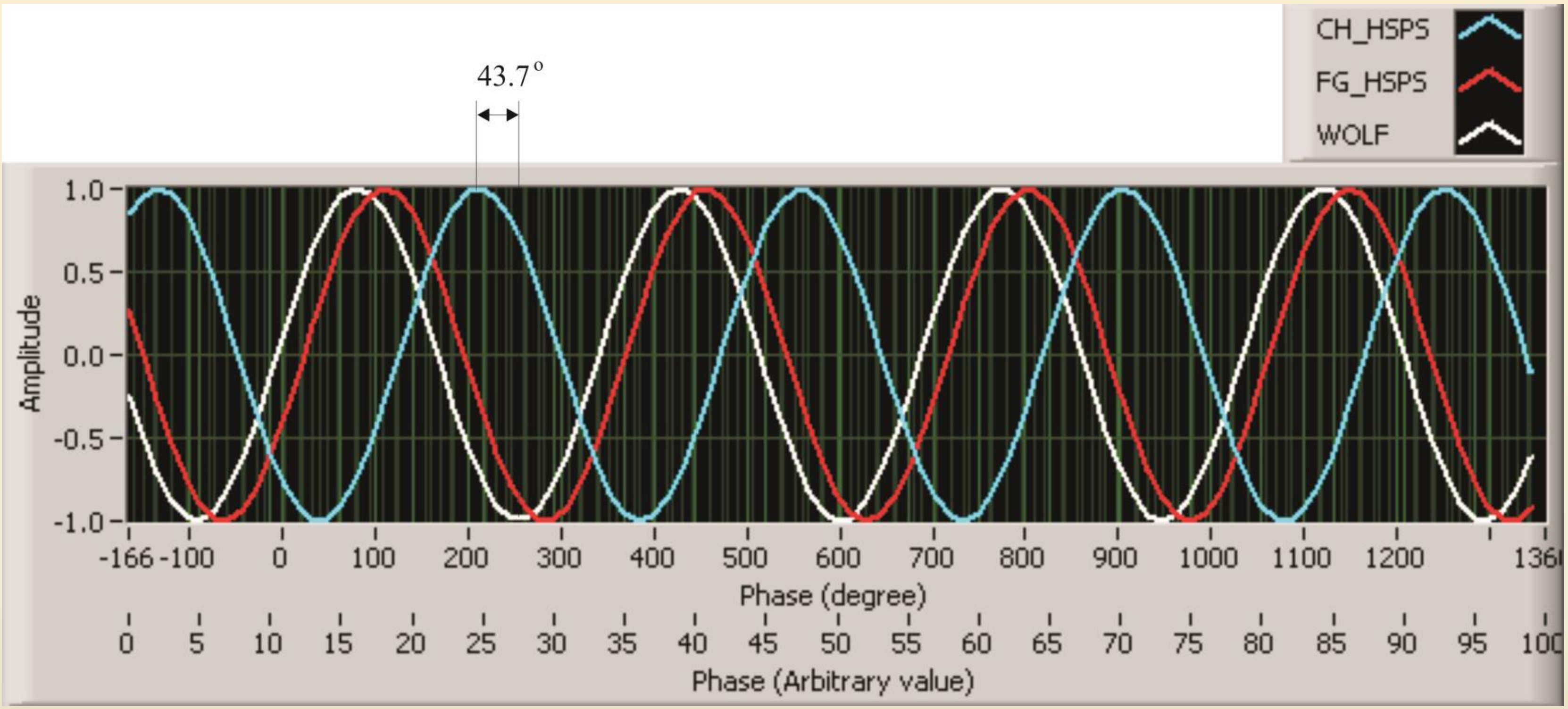
Relative minor differences between different authors result from different time interval and resolution for data series.

FFT – LabView



The phase and relative amplitude of the 11-year components for W, ΣI of CH_ and FG_HSSs

FFT – LabView



The phase and normalized amplitude of the 11-year components for W, ΣI of CH_ and FG_HSSs

Phase Shift

- The maximum amplitude of the Wolf series (W) is obtained for the spectral component of fourth order;
- With n = 4, N = 595, n_B = 27 and n_Y = 365, result a period T_4 = 11 years, the classic solar cycle;
- The same period is found in all spectra HSSs (as the maximum one or significant one, at least). It results a cyclic behavior of the HSS with the basic solar cycle (11-yr).
  - The phase of the spectral components (n = 4) are:
    - F (W) = -166.1 º
    - F (CH_HSS) = 57.6 º
    - F (FG_HSS) = 164.2 º
  - It results a phase shift between W and HSSs:
    - ΔF (W, CH_HSS) = -166.1º - 57.6º + 360º = 136,3º
    - ΔF (W, FG_HSS) = -166.1º – 164.2º + 360º = 29.7º

Phase Shift (continuation)

⇒the maximum of the CH_HSS is shifted with 136.3^{o} after maximum of the Wolf cycle, and the maximum of the FG_HSS is shifted with 29.7^{o} after maximum of the Wolf cycle;

⇒ the maximum activities of the CH_HSS are shifted with 43.7^{o} before the minimum of the Wolf solar cycle;

These shifts, converted in time, mean:

- ⇒the maximum of CH_HSSs takes place with ~4.16 years after maximum of the solar cycles, or with ~1.34 years before solar minimum;
- ⇒maximum of the FG_HSS takes place after maximum of solar cycle with ~0.9 years.

REMARKS (Conclusions)

- Spectral analysis applied on the ΣI series with 27 days (BR) resolution reveals period of 10.5 years as well as a period of 26.4 years, longer than about 22 years – the Hale cycle. Note that our interval of 1964 – 2008 contains two cycles, nos. 20 and 23, of 12 and 13 years, respectively.
- We can also notice the spectral components with frequencies which are approximately double than ones of the solar cycle (periods of 6.4, 4.1 years), which are caused by the occurrence of maximum HSS activity on the ascendant and descendant phases of each solar cycle.

Thank You

for Your attention !