Multi-wavelength radio observations as proxies for upper atmosphere modeling

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With special thanks to the instrument teams: Penticton, Nobeyama, SORCE, TIMED, Greenwich Observatory, …
f10.7
...on the shoulders of giants
Take home message 1

What I Learned From...
Take home message 1

Do not disrupt these historic observations
Look at what former generations have done...
There is an intimate connection between solar irradiance in the UV and in centimetric radio emissions...

![Radio vs UV observations](image)

S. White (1999)

6 cm (VLA)  soft X-ray (Yohkoh)
The radio spectrum in a nutshell

- Chromosphere
- Transition region
- Low corona
- Upper corona
- Interplanetary medium
The radio spectrum in a nutshell

- **Interplanetary medium**
- **Chromosphere**
- **Transition region**
- **Low corona**
- **Upper corona**

**Altitude**

- Gyro-resonance emission
- Thermal bremsstrahlung
- Plasma emissions

**Wavelength (λ):**

- 1 mm
- 1 cm
- 10 cm
- 1 m
- 10 m
- 100 m

**Emissions:**

- Gyro-resonance emission (high B) & bremsstrahlung

**Notes:**

- Source: SORCE 1/2014
The radio spectrum in a nutshell

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- Affected by terrestrial atmosphere
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The radio spectrum in a nutshell

- **Chromosphere**: Absorbed by terrestrial atmosphere
- **Transition region**: Gyro-resonance emission (high B) & bremsstrahlung
- **Low corona**: Thermal bremsstrahlung
- **Upper corona**: Plasma emissions
- **Interplanetary medium**: Affected by terrestrial atmosphere
The radio spectrum in a nutshell

- **chromosphere**
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- **low corona**
- **upper corona**
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**F10.7 index**
- plasma emissions
- thermal bremsstrahlung
- gyro-resonance emission
- gyro-resonance emission (high B) & bremsstrahlung
- affected by terrestrial atmosphere
- absorbed by ionosphere
Physical picture

- Simplified picture
  - gyroresonance ≈ essentially sunspots
  - bremsstrahlung ≈ quiet Sun + plages, faculae, ...

- The relative contribution of gyroresonance/bremsstrahlung is wavelength-dependent
Physical picture

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Could synoptic radio observations inform us about the filling factors of different solar features? ...and help reconstruct/constrain the SSI?
This picture may be too simple

- Beware: the radio spectral variability is far more complex
  - low altitude emissions may be absorbed higher up in the corona
  - optically thick vs optically thin emissions
  - non-thermal emissions (e.g. flares) are even more complex
What measurements are there?

from C. Marqué (2013)
Synoptic observations

- Observations from Ottawa/Penticton and Toyokawa/Nobeyama are exceptionally good
- daily calibration, same instruments = excellent stability
- daily values without flares (mostly) = excellent continuity

<table>
<thead>
<tr>
<th>wavelength [cm]</th>
<th>frequency [GHz]</th>
<th>origin of observations</th>
<th>beginning of measurements</th>
<th>number of gaps since beginning</th>
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<td>3.2</td>
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<td>15.0</td>
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<td>June 1, 1957</td>
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<td>30.0</td>
<td>1.0</td>
<td>Toyokawa/Nobeyama</td>
<td>March 1, 1957</td>
<td>163</td>
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</table>
A new dataset

- We now have a **homogeneous dataset** with
  - **daily values** from 6 November 1957 till today
  - **5 wavelengths**: 3.2, 8, 10.7, 15 and 30 cm
  - all values regridded to noon UT
  - without flares, data gaps filled in by expectation-maximization
  - one month latency (can be reduced to < 24 hrs)

- Download from [http://projects.pmodwrc.ch/solid/](http://projects.pmodwrc.ch/solid/)
The observations

The diagram shows the solar flux for different wavelengths (3.2cm, 8cm, 10.7cm, 15cm, 30cm) from 1940 to 2020. The y-axis represents the flux in solar flux units (sfu), ranging from 0 to 600. The x-axis represents the year, with markers at 1940, 1950, 1960, 1970, 1980, 1990, 2000, and 2010.
Analysis procedure

- Decompose the radio fluxes into [Kundu, 1965]
  - a baseline component (B)
  - a rotationally modulated component (S, or SVC)

![Graph showing the analysis procedure with three components: baseline, rotational modulation, and their sum.]
Two components

- Different wavelengths show different slopes
  = driven by different physical processes
Two components

- Different wavelengths show different slopes
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Synoptic observations

Fig. 3. Excerpt of the flux at three wavelengths with the background component, averaged over 6 months (top), and the S component (bottom). All values have been rescaled, and baselines have been shifted vertically to emphasize their tiny differences.

Therefore, the solar cycle modulation and the solar rotational modulation have distinct signatures in the radio spectrum, which also means that none of the fluxes can be expressed as linear or nonlinear function of the other. Identical conclusions had already been reached by Dudok de Wit and Bruinsma (2011) for EUV proxies.

Figure 5a, illustrates another aspect of the variability, and compares the mean amplitudes of the Band S components, as well as the modulation amplitudes of the 11-year solar cycle. The peak we observe in the S component near 10 cm has been interpreted by Schmahl and Kundu (1995) as an evidence for the prevalence of gyroresonance emissions, whereas Tapping and Detrae (1990) consider it as the signature of thermal free-free emissions. We help provide evidence for this issue in Sec. 3.

Most solar signals exhibit a strong 27-day fundamental period with a couple of harmonics. The origin of these harmonics mainly lies in the centre-to-limb variation of the emission processes (Donnelly and Puga, 1990) and in their periodic occultation. Up to two harmonics can be observed in the radio fluxes, see Figure 6, but their amplitude are considerably larger at 15 and 30 cm. This difference cannot be reasonably explained in terms of centre-to-limb variations only; the most plausible explanation is to be found in the lifetime of the solar features that contribute to the radio flux. Since bremsstrahlung-emitting features are usually longer lived than active regions, which are the primary source of gyroresonance emissions, we expect bremsstrahlung to exhibit a more coherent modulation by solar rotation, which then offers a better chance for harmonics to build up coherently. Stronger harmonics at long wavelengths can thus be seen as a indication for a greater contribution from bremsstrahlung.

All quantities have been rescaled...
Synoptic observations

Long-term variability is mostly driven by the same process: thermal Bremsstrahlung

All quantities have been rescaled
Intermediate conclusion

- Very similar variations at all wavelengths → a few contributions may explain most of the variability

- Linear combinations of different wavelengths may be used to reconstruct the SSI
e.g. [Schmahl & Kundu, 1995].
Part I

Can we isolate the different physical contributions to these synoptic radio fluxes?
Blind source separation
Blind source separation

- **Objective**: extract the original constituents ("sources") that appear mixed in the radio fluxes.
Blind source separation

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- **Assumptions**
  - linear mixing
  - the sources are mostly independent in time
  - positivity: the sources and their concentrations must be $\geq 0$
Blind source separation

**Objective**: extract the original constituents (“sources”) that appear mixed in the radio fluxes

**Assumptions**
- linear mixing
- the sources are mostly independent in time
- positivity: the sources and their concentrations must be $\geq 0$

**Solution**: use blind source separation
- used recently in acoustics, chemometry, cosmology, ...
- consider Bayesian Positive Source Separation [Moussaoui et al., 2003]
How many sources are there?

- With 5 wavelengths we can identify at most 5 sources.
- Various criteria all show that we have 3 sources.
What do the sources look like?

3.2 cm flux

10.7 cm flux

30 cm flux
Spectral profile

![Graph showing spectral profile with wavelength in cm and flux in SRF units. The graph includes three distinct profiles labeled $S_1$, $S_2$, and $S_3$. The amplitude is plotted against wavelength, with $S_1$ decreasing, $S_2$ increasing, and $S_3$ remaining constant.]
**Spectral profile**

**Source 1:** only during active Sun
- gyroresonance emissions from active regions with high B

**Source 2:** only with sunspots
- gyroresonance emissions

**Source 3:** only with plages/faculae
- Bremsstrahlung emissions
Spectral profile

Source 3 = Bremsstrahlung proxy
Power spectral density

- Power spectral density (periodogram)

![Graph showing power spectral density (PSD) with different line styles and labels for various depths (30cm, 15cm, 10.7cm, 8cm, 3.2cm). The x-axis represents frequency in [1/day] and the y-axis represents PSD in [sfu^2 * day].]
Power spectral density

- Power spectral density (periodogram)

Stronger harmonics at 30cm are not due to center-to-limb effects but to longer lifetime of emitting solar structures [Donnelly et al., 1982]
A Bremsstrahlung proxy?

How do our sources correlate with the SSI?
Data from TIMED & SORCE, 2003-2010

Source 1: gyroresonance (active Sun)
Source 2: gyroresonance
Source 3: Bremsstrahlung
How do different wavelengths correlate with the SSI?

Data from TIMED & SORCE, 2003-2010

![Graph showing correlation between different wavelengths and SSI]
Intermediate conclusions

- We have a **new Bremsstrahlung proxy** that is indeed highly correlated with the MUV-NUV bands.

- **Use the 30 cm flux** if you want a better correlation with the SSI.
  - because it has a higher Bremsstrahlung content.

- Gyroresonance emissions account for over 85% (50%) of the rotational variability at 10.7 cm (30 cm).
Intermediate conclusions

Should we consider wavelengths longward of 30 cm?
Intermediate conclusions

Should we consider wavelengths longward of 30 cm?

yes, 42 cm
Part II

Reconstruction of the SSI
Reconstruction of the SSI

The SSI can be reconstructed in various ways

- Simple empirical linear regression
  \[ I(\lambda, t) = \sum_{k=1}^{5} \alpha_k \phi(\lambda_k, t) \]

- Linear regression after decomposing into different scales (much better)
  \[ I(\lambda, t) = \sum_{\tau} \sum_{k=1}^{5} \alpha_{k,\tau} W_{\tau} \phi(\lambda_k, t) \]
Reconstruction of the SSI

Excerpt: various reconstructions
(model has been trained on a different interval)
What can we reconstruct?

- **Time scales < ~100 days**
  - XUV-NUV: excellent
  - VIS-NIR: reasonable

- **Time scales > ~100 days**
  - too early to assess (SSI data are not stable enough)
  - unlikely to work well: long-term trends may not be the same
Spinoff: stability of composites

- Reconstruction of the Lyman-α composite [LASP]
Spinoff: stability of composites

- Reconstruction of the Lyman-α composite [LASP]

![Graph showing the Lyman-α line and residual error over time. The graph displays the composite Lyman-α line from 1950 to 2020 with peaks and troughs indicating variability. Below, the residual error graph shows the difference between observations and reconstruction, with residuals around zero and some deviations.]
Part III

Impact on upper atmosphere
Impact on upper atmosphere

- Evaluate the performance by using these proxies as inputs to a satellite drag model.

- DTM (Drag Temperature Model)  [Bruinsma et al., 2012]
  - predicts temperature and composition as a function of location
  - main inputs are solar and geomagnetic forcing

- Metric of performance : \( O/C = \text{ratio of observed-to-computed neutral density} \)
Example of results

- **O/C ratio for two different solar inputs**

![Graph showing O/C ratio for two different solar inputs](image)

Mean O/C ratio DTM2012_F10 with 10.7 cm flux

Mean O/C ratio DTM2012_F30 with 30 cm flux
Example of results

- O/C ratio for two different solar inputs

Mean O/C ratio DTM2012_F10

Mean O/C ratio DTM2012_F30

- Error on O/C is on average 7% lower when 30 cm radio flux is used (instead of 10.7 cm)
Conclusions

- A homogeneous dataset of synoptic radio observations
- By statistical analysis we are able to disentangle contributions associated with Bremsstrahlung & gyroresonance emissions.
- The Bremsstrahlung proxy is excellent for MUV-NUV
- The best single proxy for EUV-NUV is the 30 cm flux

Caveats

- daily averages $\neq$ instantaneous snapshots
- flares are NOT included
- etc.
Take home message 2
Take home message 2

The spectral information of centimetric radio observations provides considerable added value to the f10.7 index
More...
Long-term trends

[Graph showing long-term trends with amplitude values from −10 to 40 for the years 1960 to 2010]

- 30cm
- 15cm
- 10.7cm
- 8cm
- 3.2cm
Contribution

S1  S2  S3  residual

30cm  15cm  10.7cm  8cm  3.2cm  ISN  DSA  MWSI  MPSI  MgII  H I  He II

contribution [%]

0  20  40  60  80  100