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The Next Generation of Canadian Solar Flux Monitoring

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Abstract. The 10.7 cm solar radio flux (F10.7), provided by the National Research Council of Canada since 1947, is widely used as an index of solar activity and as a proxy for other solar quantities that are harder to measure. Over recent years needs have arisen that are difficult to meet with solar flux measurements at a single wavelength. F10.7 comprises contributions from multiple emission mechanisms. To separate these, multi-wavelength measurements are needed. A new instrument is under construction that will measure fluxes precisely in six bands at 2.8, 3.6, 6.0, 10.7, 18 and 21 cm.

1. History and Present Status of the Radio Flux Monitoring Programme

At the end of World War II, engineers in various countries, including Australia and Canada, used ex-military radar equipment to make radio telescopes. In Canada the first radio astronomical experiments were carried out by a team headed by Arthur Covington, of the National Research Council of Canada. The instrument was derived from a radar system operating at 10.7 cm wavelength [1] with a “dish” antenna 1.2 m (4 ft) in diameter and was located in the Ottawa area (longitude W75º). Its sensitivity was poor so the only radio source that could be detected and usefully measured was the Sun.

However, carefully calibrated measurements made over many days showed the solar radio emission to vary from day to day, reflecting changes in activity inferred by other means such as sunspot number counts. This led to the simultaneous discovery by Covington [2] (at 10.7 cm wavelength) and Pawsey and Yabsley [3] (at 21 cm), in Australia, of the *Slowly-Varying* or *S-Component* of solar radio emission. In 1947 Covington, using a new instrument with a 1.8 m (6-ft) dish, began a programme of systematic daily measurements of what became known as the 10.7 cm solar radio flux, or simply F10.7, which continues today, as plotted in Figure 1. Two noteworthy features are the weakness of the present Cycle 24 and the last minimum 4 % lower than the previous ones.

The Ottawa location suffered from increasing interference. Consequently, when the Algonquin Radio Observatory (ARO) was opened in 1962 at a very radio-quiet location in a Provincial Park (longitude W78°) some 250 km from Ottawa, Covington moved the monitor there. This site offered the opportunity for additional solar radio facilities.

While operating in the Ottawa area, experiments had been carried out with multi-antenna arrays in order to make one-dimensional scans of the solar disc [4]. A larger form of this interferometer with 32 dishes each 3 m in diameter was installed at ARO on a 215 m baseline and used to make daily eastwest scans of the solar disc at 10.7 cm (2800 MHz) with a resolution a little less than 2 arcmin on the meridian. These measurements complemented Paul Wild's radioheliograph at Culgoora [5, 6], Australia, which made solar images at 43, 80, 160 and 327 MHz, showing burst sources in the solar corona.

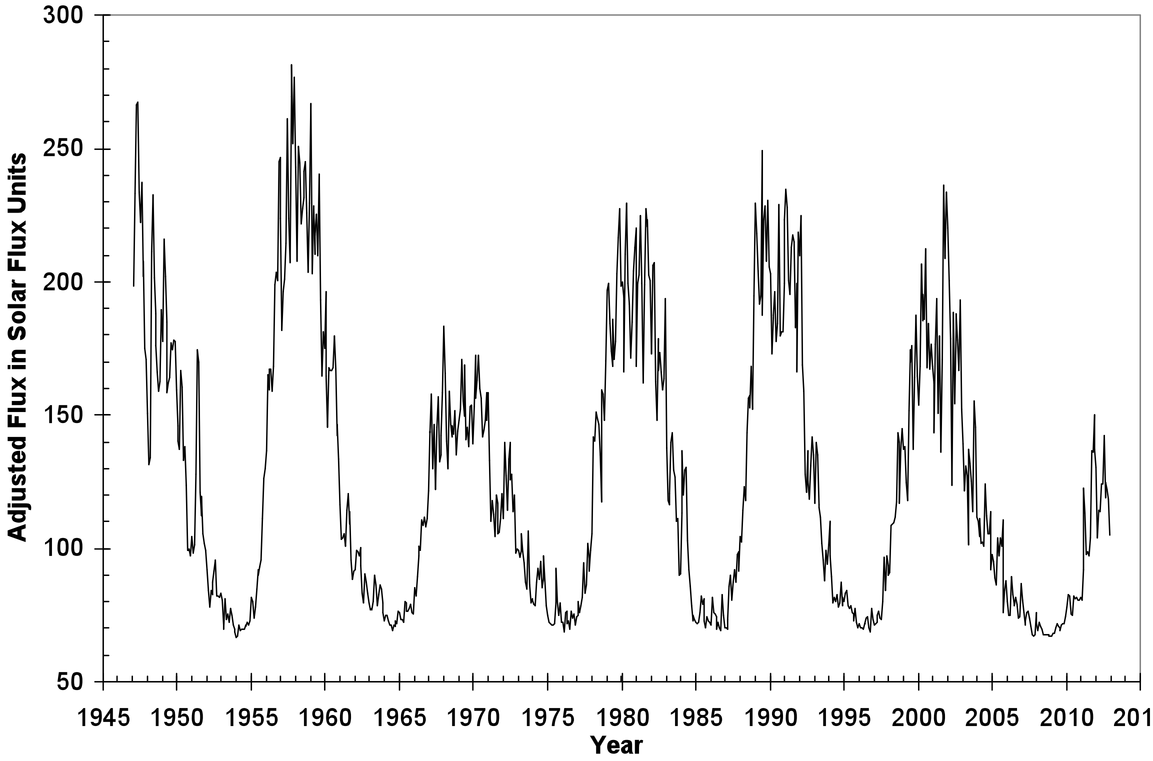

Figure 1. F10.7 monthly averages to the end of 2012 adjusted to the mean Earth-Sun distance. A solar flux unit (sfu) = 10^4 Jansky = 10^{-22} watt m^{-2} Hz^{-1}.

In the late 1980’s serious budget constraints forced the National Research Council to close the Algonquin Radio Observatory. Fortunately, the other Canadian national radio facility, the Dominion Radio Astrophysical Observatory (DRAO), located near Penticton, British Columbia (W120°), could be kept open. Moreover, there was already a solar radio observatory on-site, operating an old, backup flux monitor installed to increase time coverage. So in 1990 the Solar Radio Monitoring Programme was relocated there. The old solar instrument was removed, and a new one developed and installed. The new flux monitor was operated for several months in parallel with the ARO instrument to establish continuity of calibration and to evaluate the new instrument. The ARO instrument was then shut down and moved to DRAO, where both now are operated in parallel, to increase reliability. The radio interferometer was shut down because it was too large to move or replace.

Initially, Covington calibrated the flux measurements absolutely using a black body source that could be attached to the antenna. However, later he implemented a horn calibration standard. Simple, gently tapering pyramidal horns have the highly desirable quality that their gains (effective collecting areas) can be calculated accurately from their physical dimensions. This horn calibration standard has been refurbished and installed at DRAO, providing calibration consistency over generations of flux monitors. Several horn comparison measurements are made each northern summer when the sun has its highest altitude.

The 10.7 cm solar radio flux (F10.7) correlates with other indices of solar activity, such as the subjective, but remarkably robust sunspot number index. (See for example www.ips.gov.au.Educational/2/2/5). To a large degree these correlations are due to the overriding power of the variation of magnetic activity over the solar cycle as a modulator of solar processes. Comparisons between these indices afford a subtle means to detect changes in the solar activity cycle [7].

When Arthur Covington retired in 1978, other members of his group and their successors kept the programme running. The observations are ongoing, and the F10.7 database, extending back to 1947, is a record of solar activity of length second only to the sunspot number. The F10.7 measurements are available from the Natural Resources Canada site www.spaceweather.gc.ca/datadonnee/sol_flux/sx-4-eng.ph and the United States NOAA site www.swpc.noaa.gov//SolarCycle/f10.gif.

2. The Next Generation Solar Flux Monitor

The 10.7 cm solar flux is an excellent index of solar activity, but there are user needs that could be better met through an augmentation of this data service. First there are requirements for accurate flux values at other wavelengths that cannot be usefully derived from F10.7 values. Secondly, a major application of F10.7 is as a proxy for other important solar emissions, such as the extreme-ultraviolet (EUV) and ultraviolet (UV) fluxes. These proxies are used in modelling ionospheric processes, forecasting communication conditions, and estimating the temperature structure of the earth's atmosphere. As the applications become more demanding, there is a need to improve the proxies, or at least to better understand them.

However F10.7 comprises contributions from multiple emission mechanisms that relate differently to the proxied quantities. Emissions from flares are in principle identifiable, but in their absence F10.7 is dominated by two thermal contributions. These are free-free emission originating where the ambient magnetic fields are too weak for the electron gyrofrequency to exceed about a third of the observing frequency, and gyroresonance emission where the magnetic fields are stronger than that value. See Kundu [8] for a description of these processes. When present, thermal gyroresonance produces greater optical thicknesses and therefore brighter emission than thermal free-free emission. Therefore, at 10.7 cm wavelength, sunspots appear very bright, whereas at optical and shorter wavelengths they appear dark.

If the variations in EUV and UV fluxes are entirely due to changes in the brightness of active-region structures, proxies derived more completely from the free-free emission contribution should be more accurate. However, if the EUV fluxes are also modulated by the energy transfer through the convection zone, then a more complete indicator of magnetic activity such a mix of the two contributions, either the original F10.7 value or in some other proportion might be better. It would be of great interest to see how the relative contributions by these mechanisms to the S-component vary over the solar cycle.

The spectra of thermal free-free emission and gyroresonance are very different. The free-free emission shows a monotonic decrease with increasing wavelength, whereas thermal gyroresonance from solar active regions has a broad peak due to the superposition of many resonances, but drops to low values both at short wavelengths due to rapidly falling optical thickness and at long wavelengths where it is blocked by the overlying optically thick free-free emission. Tapping and DeTracey [9] showed that the spectrum of solar free-free emission is relatively insensitive to different coronal density models but sensitive to the density at the base of the corona. This suggests that a fit to identifiably free-free contributions to the S-Component spectrum would remove most of the free-free contribution, leaving that due to gyroresonance. In Figure 2, the green curve is a modelled spectrum of the quiet sun emission, assumed to be totally free-free. The black curve represents a spectrum of a more active Sun, assembled from observations. By increasing the density at the base of the corona the free-free curve can be made to fit the observed spectrum at the long and short wavelengths, where the emission may be assumed to be completely free-free (blue curve). By subtracting that spectrum from the total, we obtain the contribution due to gyroresonance (the red curve). This procedure would not be practical for individual active regions, but should work with the integrated emission from all sources present on the solar disc.

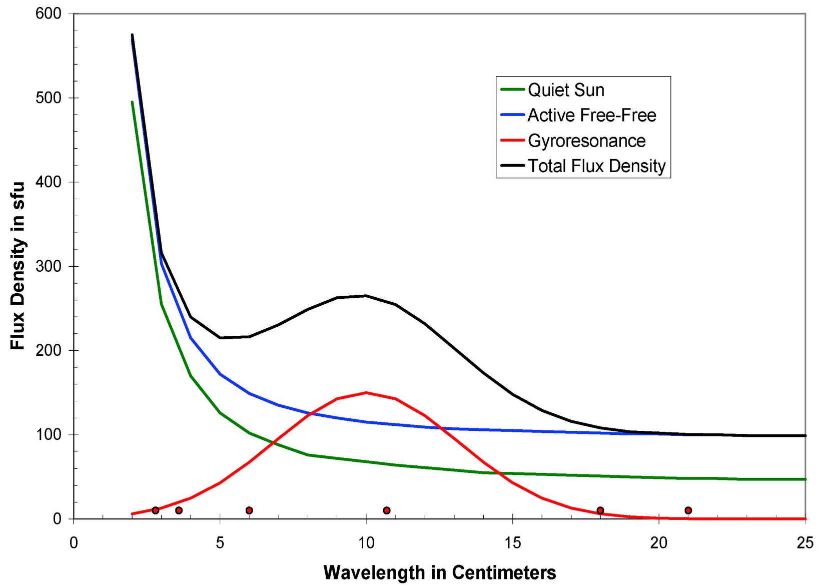

Figure 2. Schematic spectra showing total flux (black), free-free quiet sun emission (green), this emission scaled to fit the total flux at long wavelengths (blue), and the gyroresonance contribution (red).

In practice, resolving the components will require precise flux density measurements at several wavelengths made in exactly the same manner, at the same time and, as much as possible, using the same hardware. In addition to meeting user needs for flux values at additional wavelengths, this spectral decomposition was the rationale for the development of the multifrequency "Next Generation Solar Flux Monitor" (NGSFM) currently under construction at DRAO.

The specifications for the system are as follows:

1) Solar fluxes will be measured at 6 wavelengths: 21cm (1415, 20 MHz), 18 cm (1660, 10 MHz), 10.7 cm (2800, 100 MHz), 6.0 cm (4995, 50 MHz), 3.6 cm (8.3 GHz, 50 MHz), 2.8 cm (10.6 GHz, 100 MHz), where the figures in the parentheses are respectively the frequencies corresponding to the observing wavelengths and the receiver bandwidths. Once the NGSFM is in operation and its performance has been evaluated, some wavelengths might be changed and longer wavelengths added to more effectively sample the spectrum.

2) All frequencies will be measured at 1000 samples/sec to provide precise observations of solar bursts and other transient events.

3) Duplicate equipment will use orthogonal linear polarizations from the antenna feed to achieve redundancy in the observations.

4) Seven different calibration noise levels will be used on each channel in order to monitor linearity and to increase the chance of a calibration level being close to the solar noise level being measured.
5) To measure the total flux from all the emissions from the solar disc, the antenna beamwidth must be at least 3.5 degrees (for a Gaussian beamshape) over the whole operating wavelength range. To do this the feed will progressively under-illuminate the dish with decreasing observing wavelength. The antenna is a 3.7 m (12-ft) dish that was originally used for geophysical VLBI observations by Natural Resources Canada.

To better observe the spectral structure in solar bursts and other emissions, a team headed by Professor David Thompson (Queen's University, Kingston, Ontario) will provide a radio spectrometer covering the 30 - 2.5 cm wavelength range. This also could provide fill-in information that can be used with the flux measurements to construct the whole spectrum.

Each of the orthogonally polarized broadband signals from the focus will be individually amplified without any filtering or bandwidth limiting and fed to two identical receiver modules mounted on the back of the dish. In each module the signal will be split into eight identical channels. Six of them will be fed to the receiver modules, one for each observing wavelength, one of the remaining two channels will be fed to the Queen's University spectrometer; the other will be a test output.

Calibration of an under-illuminated paraboloidal antenna is particularly difficult, so this will be done using an array of horn antennas on a common mount, making absolute flux determinations at all six wavelengths. It is anticipated that the NGSFM will start operation in 2013 with calibrated flux values being available about a year later.

Ground-based solar monitoring has the advantages over monitoring from space-based platforms that they are comparatively inexpensive, very flexible and easy to keep running for a long time. However, they have the disadvantage that continuous, 24-hour coverage is impossible from any single location. Consequently we are actively collaborating with the Royal Observatory of Belgium and communicating with additional ones, with the objective of having several similar or identical instruments distributed in longitude around the world.

Acknowledgments
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References
[1] Covington A E 1952 NRC 10.7-centimeter radio telescope and radiometer *NRC Report* **ERA-216**, National Research Council of Canada
[2] Covington A E 1948 Solar radio noise observations at 10.7 cm *Proc IRE* **36** 454
[3] Pawsey J L and Yabsley D E 1949 Solar radio-frequency radiation of thermal origin *Australian J. Scientific Research - Series A* **2** 198
[4] Covington A E and Broten N W 1957 An interferometer for radio astronomy with a single-lobed antenna pattern *Transactions IRE Antennas and Propogation* **AP-5** 247
[5] Labrum N R 1972 The Culgoora solar radio observatory *Solar Physics* **27** 496
[6] Frater R H and Ekers R D 2012 John Paul Wild 1923 - 2008 *Historical Records of Australian Science* **23** 212
[7] Tapping K F and Valdes J J 2011 Did the sun change its behaviour during the decline of cycle 23 and into cycle 24? *Solar Physics* **272** 337
[8] Kundu M R 1965 *Solar Radio Astronomy* (New York: Wiley-Interscience) Chapters 5 and 6
[9] Tapping K F and DeTracey B 1990 The origin of the 10.7 flux *Solar Physics* **127** 32