Quasi-Periodicity in global solar radio flux at metric wavelengths during Noise Storms.

G.A. Shanmugha Sundaram$^{1,2}$ (sga@physics.iisc.ernet.in) and K.R. Subramanian$^2$ (subra@iiap.res.in)

1. Joint Astronomy Programme, Department of Physics, Indian Institute of Science, Bangalore - 560012, Karnataka, INDIA.

2. Indian Institute of Astrophysics, Bangalore - 560034, Karnataka, INDIA.

March 24, 2004

Abstract. We present observational results from studying the quasi-periodicities in global solar radio flux during periods of enhanced noise storm activity, over durations of $\sim$ 4 hrs a day ("intra-day" variations), observed at 77.5 MHz with the newly commissioned log-periodic array tracking system at the Gauribidanur radio observatory. Positional information on the storm centers were obtained with the radio imaging data from the Nançay RadioHeliograph (NRH), while their active region (AR) counterparts on the photosphere (and the overlying chromosphere) were located from the $H\alpha$ images of the Big Bear Solar Observatory (BBSO). The quasi-periodicity in flux was found to be 110 minutes, with the fluctuation in flux being $3(\pm 1.5)$ solar flux units (sfu). The results of such pulsations are interpreted qualitatively as evidence for coronal seismology.

Keywords: corona, radio, noise storms, quasi-periodicity, pulsations, seismology

1. Introduction

Type I solar noise storms, ever since their discovery in the year 1946 (Hey, 1946), have proved to be amongst the most prolific of events to occur at metric wavelengths. They comprise of the bursts that are radio flux enhanced, narrowband ($df/f \approx 3\%$), spiked (0.1 - 1 s) events, with the broadband ($df/f \approx 100\%$) continuum, lasting from several hours to a few days, serving as their diffuse background radio emission, on the dynamic spectral records. According to (Hey, 1946), (McCready, Pawsey, & Payne-Scott, 1947), noise storms have their origins in the outer corona, and appear proximal to the sites of active regions in the photosphere and the chromosphere.

In this paper, we present results from investigations on the variations of global radio flux, during periods of prolonged noise storm activity, with attributes to quasi-periodicities on short time scales, from observing the
Sun continuously for about 6 hrs each day. Details on the time-delay control enabled, broadband operable antenna array system used for the study are provided, followed by a note on the observation schedule adopted. Interpretation of the imaging data from complementary observations on the noise storms and the associated underlying ARs constitute part of the latter section. The scheme deployed to analyse and determine the extent of global radio flux variations is described in §4. The results of this study are presented in the Discussion & Conclusion section, along with qualitative remarks on the plausible origin for the observed flux oscillations at metric wavelengths, and their likely coronal implications.

2. Antenna Instrumentation

The Gauribidanur Radioheliograph (GRH (Ramesh et al., 1998)) is a transit-mode instrument, while the time-delay control implemented on the Gauribidanur Prototype Tracking System (GPTS) to GRH, enables the Sun to be followed as it traverses the sky. The antenna system comprises one group each along the (E-W) and (N-S), as with the GRH, forming an L-shaped \((8 \times 4)\) element log-periodic dipole antenna (LPDA) array, interconnected in a X-mas tree topology by radio frequency (RF) cables. The delay-tracking scheme has been implemented on its front-end electronics, and involves a network of delay-line cables and signal-loss compensating attenuators; this would eliminate the otherwise cumbersome task of mechanically steering the LPDA array, while also permitting radio observations over a significantly wider frequency band. The observing frequency was set at 77.5 MHz, and this choice was based on the relatively terrestrial-interference-free signals that were acquired over the entire observing duration.

Automated PC-based control and monitoring of the tracking process was deployed for an entire session of radio observations (spanning about 4 hours), so as to achieve a precise "dwell-time" between adjacent beam-positions, in accordance with a look-up table, while also serving to implement the "\(\delta\)-setting", so as to attune the response of the array to the declination (\(\delta\)) of the source under study.

The receiver system was of the analog superheterodyne type, with a square law detector and a PC-based acquisition system constituting the data detection, digitization, real-time display, and storage entities.
3. Observations

Continuous solar observations were made at 77.5 MHz, over the period from 24th June, 2002 to 20th August, 2002, with gaps in the observations at some beam positions on a few days, assigned zero flux values subsequently. The daily schedule involved solar observations at seven successive beam-positions, comprising zenith-angles from 27° E to 27° W, in equiangular steps of 9°, on either side of the local meridian at Gauribidanur, for about four hours each day. A "sit-and-stare" method of acquiring the solar profile was adopted, while the Sun drifted through the beam pre-deployed at a particular position, as the in-phase and quadrature-phase components, to yield the signal intensity as a convolved pattern of the Sun's disk and the array power pattern.

Absolute solar radio flux calibration was performed, by following an identical observing schedule for the intense, unresolvable radio source like Cygnus A, Cas A, Crab, or Virgo, whose flux-densities are reliably known (Baars et al., 1977). This procedure, while translating the total power acquired by the receiver (in arbitrary units of signal intensity), for a given set of solar observations, in terms of radio flux (in janskys or sfu), also ensures that the gain variations, observed during tracking of the Sun at all seven beam positions, are effectively equated at each such position. The beam position dependent gain-variations are a result of ohmic losses in the passive components on the delay-cards, frequency-dependent phase characteristics of the RF cable that vary as a function of the beam position, and localized attenuation/phase variations in the RF cable characteristics.

The dwell-time ($t_d$) is defined as:

$$t_d = t_e \times \sec(\delta) \quad s.$$  

where ($t_e$) is the period per degree of angular rotation in seconds (1° = 4 minutes of time, for $\delta = 0^o$). Successive beams were positioned every $t_d$ minutes, as the radio source changes in hour-angle, with the data being acquired concurrently. This method was followed for about two months, during which period the activity of the radio Sun underwent significant changes, as is evident from Figure 1. The plot depicts the calibrated solar radio flux (obtained from averaging the data-samples about the transit point of individual profiles), as each data point, for a consecutive span of 58 days, with each day's stake being 7 successive data sets (from observations made at the 7 beam positions everyday). The data points were obtained as a difference between the mean of 50 points in the total-power envelope, symmetrically.
determined from tracking of the Sun consecutively from 24th June 2002 to 20th August 2002; successive 7 data points constitute a single day’s observation. The four epochs of enhanced radio emission are indicated by I, II, III, & IV. The start- and end-dates of the total observing schedule are indicated on the lower-left and right corners, in the (dd/mm/yyyy) format.

distributed about the transit point, and the median of 50 data points of the profile-baseline. In almost all cases where the radio flux attains a value of 0 sfu, the absence of observational data at the corresponding beam-position is being cited as the reason.

The antenna-receiver performance characteristics were evaluated extensively during the period, that comprised of extended quiet-Sun epochs interspersed with solar activity, as a function of beam-position in the end-to-end tracking window. Since the LPDA array for the prototype tracking system has a group-beam size of $\sim 2.98$ (more than the solar disk-size at 77.5 MHz), a variation in the radio flux, due to any particular solar radio activity, would have attributes on a global scale, since the fine-structure components associated with isolated regions on the solar disk are bound to be smudged-out by the wider beam. Days of heightened solar radio emission, measured from the enhanced global radio flux, were segregated for study of their periodicity and distribution characteristics.
3.1. Complementary observations

Type I noise storm exhibit an increased tendency to occur above bipolar active sunspot groups, with specific accent on the maximum area occupied by a bipolar sunspot or the spot-group, and the active region complexity as regards its magnetic topology (Elgarøy, 1977) and references therein). Studies performed by (Dodson & Hedeman, 1957) and (Dulk & Nelson, 1973) on such a correlation, suggest values of area associated with a sunspot group as low as a 100 millionth of that of the solar disk, as the minimum requirement.

According to (Brueckner, 1983), all type I noise storms observed during the Skylab period were caused by changes in the coronal magnetic field structure, and all coronal magnetic field changes observed on the disk were correlated with newly emerging flux; the storm source was found to lie in the closed loop of strong magnetic fields, just above the associated active region. Hence it is clear that the existence of a sunspot or a group of sunspots is a necessary condition for the generation of noise storms.

The noise storm radiation has been known to attain a sharp maximum near the Central Meridian Passage (CMP) of a large sunspot group, thereby revealing the sharply defined directivity characteristics. The radiation has its origins within an area on the Sun’s disk, that is of the same order in size and angular position-coordinates to that of the associated spot-group (Wild, 1950) & references therein). Full-disk Hα images, from observations made at the BBSO, reveal the presence of large and complex ARs underlying the regions of enhanced noise storm radiation; the temporal correlation between the CMP of the former with the emission of the latter is the most noteworthy.

In order to further illustrate the temporal association, data from the GPTS, averaged over seven successive beam-positions (daily mean flux), is depicted alongside the daily mean total solar radio flux measurements obtained at 245 MHz (adjusted to 1 A.U.) by the Sagamore Hill Observatory, Massachusetts, USA and published as ”Daily Solar Indices” in the Solar Geophysical Data (SGD - prompt reports), for the same period. Taking due cognizance of the missing data points in the GPTS data, and the differing coronal processes at varying plasma levels (that correspond to 77.5 MHz and 245 MHz), the temporal correlation between the two sets of data is very evident over the period considered for study. A quantitative analysis for correlation, with reference to the two plots in Figure 2, yielded values for their coefficients of 0.78, 0.8,
Figure 2. Daily mean total-Sun radio flux at 77.5 MHz (GPTS: upper plot), and 245 MHz (Sagamore Hill: lower plot) from 24th June to 20th August, 2002. The four epochs of global flux enhancement are denoted by I, II, III, & IV. Along the x-axis, spacing between adjacent dates constitutes a span of one week (7 days).

0.96, & 0.56 for the four periods (viz., I, II, III, & IV) of enhanced radio-flux emission - indicative of a fairly reasonable correlation.

4. Data Analysis

Table I.(i) lists-out the salient characteristics of the large ARs observed on the full disk $H\alpha$ images of BBSO. The first column gives the USAF/NOAA active region number, the II set of columns stand for the dates of occurrence (during the period of the noise storms considered) of the ARs (their initial appearance on the East limb, cross-over at the Central Meridian and the last appearance on the West limb). The III & IV columns give the coordinates of the AR-centroid and the longitudinal extent about the centroid in degrees, during the entire span in days, elapsed since their appearance and traversal of the solar disk, as mentioned by the extremity dates of column II. The data add greater significance to the earlier works cited in §3.1, regarding the extent and location of the noise storms vis-a-
| NOAA AR No. | Initial (E-limb) | CMP | Last (W-limb) | Sunspot-group | Long. spread | Max. spot | Area $10^{-6} \, A_\odot$ |
|-------------|------------------|-----|---------------|---------------|--------------|-----------|------------------|
| 10030       | 9 July           | 15/16 July | 22 July | N (15-23) | (2-23) | 91 | 1430 |
| 10039 / 10044 | 22 July          | 28 July | 3 August | S (12-18) | (5-21) | 90 | 1447 |
| 10061       | 3 August         | 9/10 August | 15 August | N (05-11) | (2-13) | 66 | 390 |
| 10069       | 11 August        | 17/18 August | 23 August | S (05-10) | (3-17) | 95 | 2669 |

Table 1: (i) Salient characteristics of the Noise Storm associated Active Regions.
Table I. (ii) Salient characteristics of the Noise Storm associated Active Regions, observed on the dates of CMP, with the NRH and GPTS.

| Date of CMP (2002) | Heliographic Positions (E-W) (Mean Values) (N-S) | NRH GPTS |
|-------------------|-----------------------------------------------|----------|
| 15/16 July        | 25 W                                          | 21 N     | 20-300 | 6.65 |
| 28 July           | 13 W                                          | 18 S     | > 300  | 7.4  |
| 9/10 August       | 5 E                                           | 7 N      | 100-300| 11   |
| 17/18 August      | 28 W                                          | 31 S     | ~ 300  | 10.76|

vis that of the underlying ARs, especially since the coronal structures are magnetically confined to and rigidly towed along by the underlying photospheric features (Aschwanden & Bastian, 1994). Column V & VI list the maximum number of sunspots and area attained in the ARs. The area comprising each of the sunspot groups is seen to be far in excess of the minimum criterion (which is a 100 millionth of that of the projected visible solar hemispherical disk) for the underlying active region to be closely attributed to metric type I noise storm radiation. The number density of the sunspots and the area occupied on the solar disk are indicative of the complexity of the AR; this, and the dates of CMP of storm centers at the coordinates indicated in Table I.(ii), strongly suggest a spatio-temporal association of the ARs with the global flux enhancements due to the noise storms as shown in Figure 1.

During the entire observing schedule spanning 58 days (of ~ 4 hrs each day), periods of enhanced global solar radio emission were detected over several days. They were grouped into four prominent phases of enhanced solar radio flux, corresponding to prolonged noise storm activity at the coordinates shown in Table I.(ii), from Nançay Radioheliograph
Quasi-Periodicity in Active-Sun radio flux

Table II. Temporal coincidence in the NRH and GPTS observing times.

| Date of CMP | Observing Time ( U.T.) |
|-------------|------------------------|
| ( 2002 ) | NRH ( 164 MHz ) | GPTS ( 77.5 MHz ) |
| | | ( h.a.=27º W ) |

16 July 09:41:58 09:47.67 28 July 09:41:53 09:48.33 9 August 09:40:49 09:43.44 18 August 09:39:47 09:40:00

observations at 164 MHz. The table also gives details on the dates of CMP of the associated ARs underlying the metric noise storm sources, their heliographic positions and calibrated peak flux estimates in sfu, for the NRH and GPTS data.

A unique temporal coincidence exists for the observations made by the NRH at 164 MHz, with that of the last beam-position ( hour angle ( h.a.) = 27º W ) of the GPTS at 77.5 MHz ( Table II ), thereby providing a direct means of spatially ( and by virtue of their near-similar observing times, temporally ) associating the radio flux enhancement, observed in the GPTS data, with the particular event recorded as two dimensional imaging information by the NRH. As is discernible from Table I.(ii), the flux values detected by either of the instruments allude to the noise storm events of 16th & 28th of July and 9th & 18th of August, 2002. Temporal coincidences with spectral observation on type I noise storms at metric wavelengths, made by Potsdam, Izmiran & Culgoora observatories, and listed in the Solar Geophysical Data : Prompt Reports - (SGD, 7/2002), (SGD, 8/2002) & (SGD, 9/2002), corroborate the observations made with the tracking system during this period of solar activity.
Figure 3. Scatter-plots of absolute deviation from mean solar radio flux (in janskys) with beam-position of GPTS on days of activity (28 July, and 7, 9 & 10 August 2002); the solid line is a cubic-spline interpolation fit to the data points.

With the threshold level, for classifying a particular data point as being an instance of noise storm activity, against a flux-poor background, set at 5 sfu, the total number of days of enhanced noise storms was found to be 17, or a total of 119 data points. On each of those days, the absolute deviation from mean flux (chosen to be the mean value for radio flux about transit, among the seven beam position on that day) was plotted as a scatter-plot, as in Figure 3. Curve-fitting, by cubic-spline interpolation performed on the data points, reveals 32 cases of quasi-half-periods for absolute deviation from the mean values.

5. Discussion & Conclusion

The general consensus on the radiation mechanism of noise storms is one of plasma emission. New emergence of magnetic flux, and the
changes in the topography of the magnetic field arising out of the reconnection (Benz & Wentzel, 1981) of ruptured, preexisting flux lines with the newly sprouting flux, about the sites of bipolar sunspot activity, leads to the formation of recurrent shock waves (Spicer, Benz, & Huba, 1981), (Wentzel, 1981). The electrons of the ambient plasma within the reconnection loop, at the outer coronal layers, become unstable as a result of this realignment of magnetic lines of force, and generate the Langmuir (L) waves or the Upper hybrid (UH) waves. Such L-waves and UH-waves coalesce in turn with the ion acoustic waves, at the sites of density inhomogeneities, to emit the type I continuum noise storm radiation. On the other hand, bursts of type I are produced when the UH-waves, produced by the electrons trapped in magnetic flux loops, are scattered on the Lower hybrid (LH) waves generated at their shock wavefront.

The determination of quasi-periodicity is subject to a lower cut-off, defined by the beam dwell-time. The adjacent beam positions are $9^\circ$ apart, and the dwell-time varies as a function of the apparent declina-
tion of the Sun, in a manner defined by Equation (1), where \( t_c \) is 36 minutes, and \( \delta \) varied from 13.2° N to 23° N. Hence, \( t_d \) is the minimum value for quasi-periodicity that can be realised by the tracking system in its current scheme of observation. The quasi-periodic distribution, for the 32 cases of absolute deviation from mean, is shown in the histogram of Figure 4. The peak in the distribution occurs at 110 minutes, which also is tantamount to the periodicity in global solar radio flux variation at 77.5 MHz. In addition, more than half (\( \approx 60\% \)) of the distribution occurs in the range of periodicities from 100-150 minutes.

Regarding the spline interpolation method employed for determination of the absolute deviation from mean (shown in the four sub-plots of Figure 3), it needs to be duly emphasised that vast deviations, occurring on either side of the mean and at consecutive beam position observations, are bound to yield quasi half-periodicity values lesser than the minimum achievable "cadence" between the two adjacent observations on the same day - a case of so-called "super-resolution", that needs to be cautiously approached, especially when the distribution were to peak at those values. In Figure 4, the first couple of values in the vicinity of 50 min are the case in point, corresponding to the first negative going half-waveforms on the upper-right and the lower-left sub-plots of Figure 3; they have values for quasi-periodicity less than the \( t_d \) defined by Equation (1) for the particular days.

Quasi-periodic fluctuations in solar coronal emission, observed at the operating frequencies of the antennas on-board the Prognoz 1 high-apogee satellites (Grigoreva, Pugacheva, & Shestopalov, 1977) equipped with kilometric radiation detectors, have estimated periods ranging from 6 sec to 2 hours. A specific quasi-periodicity value of 118 (\( \pm 20 \)) minutes has been quoted among many other values detected, for fluctuations in radio emission by 10-15 dB from the mean solar flux. In the present study done at 77.5 MHz, the quasi-periodic fluctuations have an absolute deviation from the intra-day mean ranging from 1.5 to 4 sfu.

The absolute deviation from mean flux, for each of the 17 days of enhanced activity, is taken as a measure of the intra-day quasi-periodicity in solar radio flux, and found to be 110 minutes, with the fluctuations in flux being 3(\( \pm 1.5 \)) sfu. Positional information from the Nançay Radio-Heliograph data, and features of the causative ARs of the underlying photospheric disk from the full disk \( H\alpha \) images of the BBSO, along with the radio spectral data published in the SGD reports, lead to the conclusion that heightened flux emission, with global ramifications, are a result of type I noise storms.
The occurrence of the noise storm source regions, and their contribution to enhanced radio emission on a global scale, has been corroborated from complementary evidence based on active region data obtained from the BBSO full disk Hα images, the NRH’s 164 MHz imaging data on noise storms and the metric noise storm spectral observations as reported in the SGD reports. Quasi-periodic pulsations in global solar radio flux were observed, and their origin has been attributed to modulation of the plasma radiation by magnetohydrodynamic (MHD) disturbances in the corona, at sites above large ARs threaded by complex magnetic flux tubes. MHD disturbances are generated by the weak shocks associated with magnetic reconnection events, as MHD oscillations or resonance of MHD waves, and fluctuations (pulsations) in the plasma radio emission ensue at the source region for noise storms. MHD waves on all scales, ranging in wavelength from the coronal loop-size (fraction of $R_\odot$) down to the gyroradii (a few meters) of coronal ions, are believed to play a key role in the transport of mechanical energy, from the denser regions of the chromosphere to the Sun’s corona and further as a steady stream called the solar wind; by means of dissipation of the wave energy, the corona is heated and sustained at elevated temperatures. The emissivity of trapped epithermal particles in coronal magnetic arches is modulated by a propagating MHD wave (Aschwanden, 1987). In the case of noise storms, the plasma waves get converted to transverse electromagnetic (TEM) waves at sites of trapped density inhomogeneities and magnetic reconnections. Theoretical interpretation of the oscillatory phenomena, observed in the outer solar corona, based on the MHD wave theory, along with supportive information, regarding the plasma parameters, from investigation of high spatial and temporal imaging data on the coronal magnetic structures above the active region complexes, would significantly demystify the underlying mechanisms involved in the plasma dynamics of the outer corona, coronal-seismology and coronal-heating.

**Acknowledgements**

We thank the scientific and technical staff of the Gauribidanur Radio Observatory, and the Nançay Radioheliograph team at the Unite Scientifique de Nançay (Station de RadioAstronomie de Nançay, 18330 Nançay, France) of the Observatoire de Paris for use of their 2D radio maps. We also thank the referee for insightful comments which improved the content and presentation of this paper. The Solar Geophysical Data Reports are published by the National Geophysical Data
Shanmugha Sundaram & Subramanian

Center, NOAA, 325 Broadway, Boulder, Colorado, 80305-3328 USA. The \( H\alpha \) images were obtained from the FTP Data Archive and World Wide Web pages of the Big Bear Solar Observatory/New Jersey Institute of Technology, 40386 North Shore Lane, Big Bear City, CA 92314 USA.

References

Aschwanden, M. J.: 1987, Solar Phys. 111, 113.
Aschwanden, M. J. and Bastian, T. S., 1994, Astrophys. J 426, 434.
Baars, J. W. M., et al.: 1977, Astron. Astrophys. 61, 99.
Benz, A. O. and Wentzel, D.G.: 1981, Astron. Astrophys. 84, 100.
Brueckner, G. E.: 1983, Solar Phys. 85, 243.
Dodo, H.W. and Hedeman, E.R.: 1957, Astrophys. J 125, 827.
Dulk, G.A. and Nelson, G.J.: 1973, Proc. Astr. Soc. Aust. 2(4), 211.
Elgaroy, O.: 1977, Solar Noise Storms (Oxford: Pergamon).
Grigoreva, V. P., Pugacheva, G. I. and Shestopalov, I. P.: 1977, Geomagnetism and Aeronomy (Trans.) 17, 221.
Hey, R.: 1946, Nature 157, 47.
McCready, L.L., Pawsey, J.L. and Payne-Scott, R.: 1947, Proc. Roy. Soc. (A) 190, 357.
Ramesh, R., et al.: 1998, Solar Phys. 181, 439.
Solar-Geophysical Data prompt reports, July 2002, 695 - Part I.
Solar-Geophysical Data prompt reports, August 2002, 696 - Part I.
Solar-Geophysical Data prompt reports, September 2002, 697 - Part I.
Spicer, D.S., Benz, A.O., and Huba, J.D.: 1981, Astron. Astrophys. 105, 221.
Wentzel, D.G.: 1981, Astron. Astrophys. 100, 20.
Wild, J. P.: 1950, Aust. J. Sci. Res. A4, 36.

Address for Offprints: G. A. Shanmugha Sundaram
Joint Astronomy Programme
Department of Physics
Indian Institute of Science
Bangalore - 560012
Karnataka
INDIA