# Short-haul communications using NVIS HF radio

**by S. J. Burgess and N. E. Evans**

In geographical regions poorly served by land-lines or line-of-sight repeaters, high-frequency (HF) radio can still provide a low-cost alternative to satellite links. In particular, the near vertical incidence sky-wave (NVIS) propagation mode gives omnidirectional coverage from a central site; 300 km ranges are possible and the technique has an inherent ability to fill in 'blind spots' lying in hilly ground. Normal voice and data services may be readily established. This paper introduces NVIS radio, discusses some of its roles to date and examines the hardware required for basic link implementation; emphasis is placed on antenna design and selection. Channel availability and fading characteristics (depth and frequency) gathered from a 6793 kHz oblique sounder over the 1997/8 winter–summer transition are included to illustrate the potential of the technique for non-real-time remote monitoring applications.

## 1 Using HF radio

For many years HF radio (3–30 MHz) has been used as a means of providing long- and short-haul communications, the former having ranges of up to thousands of kilometres and the latter tens of kilometres[1]. It is common practice in short-haul work to rely on space waves that remain in the lower atmosphere. The attenuation levels experienced by these 'lower atmospheric' waves depend upon the type of terrain which they traverse and any obstacles encountered. Long-haul HF communication involves initially launching radio waves at the ionised regions (also referred to as layers) above the earth — the ionosphere; progressive refraction causes bending of the wave, ultimately leading to its return to earth (see Fig. 1). The principal source of radiation that contributes to the ionosphere's existence is the sun. Hence, it comes as no surprise that various phenomena occurring in and around the sun's atmosphere have been shown to directly affect HF ionospheric propagation conditions on earth.

*The ionosphere: a zero cost reflector*

The salient difference between point-to-point VHF/UHF links (including satellite) and HF sky-wave systems is that in the latter an active rebroadcast element (i.e. some form of repeater) is not needed. The ionosphere forms a 'natural' passive repeater, or reflector, provided by the sun: it is essentially considered as a cold and weakly ionised gas (a plasma) with the earth's magnetic field superimposed (giving a magnetoplasma). For ionospheric study purposes the plasma consists of equal numbers of electrons and single positive ions (it is electrically neutral). In a plasma, electrons can oscillate about the heavy ions and physically spiral around the external magnetic field flux lines. An incident radio wave causes the electrons' oscillation amplitude to increase, with the subsequent energy absorption and reradiation leading to refraction; the critical frequency of a plasma layer is related to its peak electron density $N_{max}$ by the relationship:

$$f_C \approx 9\times10^{-6} N_{max}^{0.5} \quad (1)$$

If the frequency of an incident wave exceeds $f_C$ for a particular region, electrons within it will not be 'excited.' As a result the wave passes through the layer without refraction and a sky-wave link cannot be established.

The properties and behaviour of the ionosphere are neither constant nor precisely defined. Eqn. 1 gives only an approximation of the upper frequency limit; other determining factors include variability in the earth's magnetic field with latitude and solar particle bombardment. Significant trends in refraction frequencies have been noted to be cyclic in time. The sun, in essence, is a large gaseous body and as it rotates a differential surface change occurs across its face. There is a resultant distortion and twisting of its magnetic field, with large bipolar loops appearing above and below the central meridian line in what is known as its photosphere. The photosphere is best viewed in white light: the protruding bipolar loops are cooler and consequently appear as 'dark spots', contributing to performance as reasons for choosing alternative propagation techniques.

## 2 Introducing NVIS

In certain applications a specialised form of HF sky-wave link can be advantageous. For example, conventional line-of-sight (LOS) systems can have a repeater rendered inoperative as a consequence of a natural disaster. A satellite link can be destroyed by an adversary in times of war or there may be zero availability of such 'modern' systems, as is the case in many underdeveloped regions of the world. In such circumstances viable short-haul communications may be provided using obstacle-independent, near vertical incidence sky-wave (NVIS) propagation.

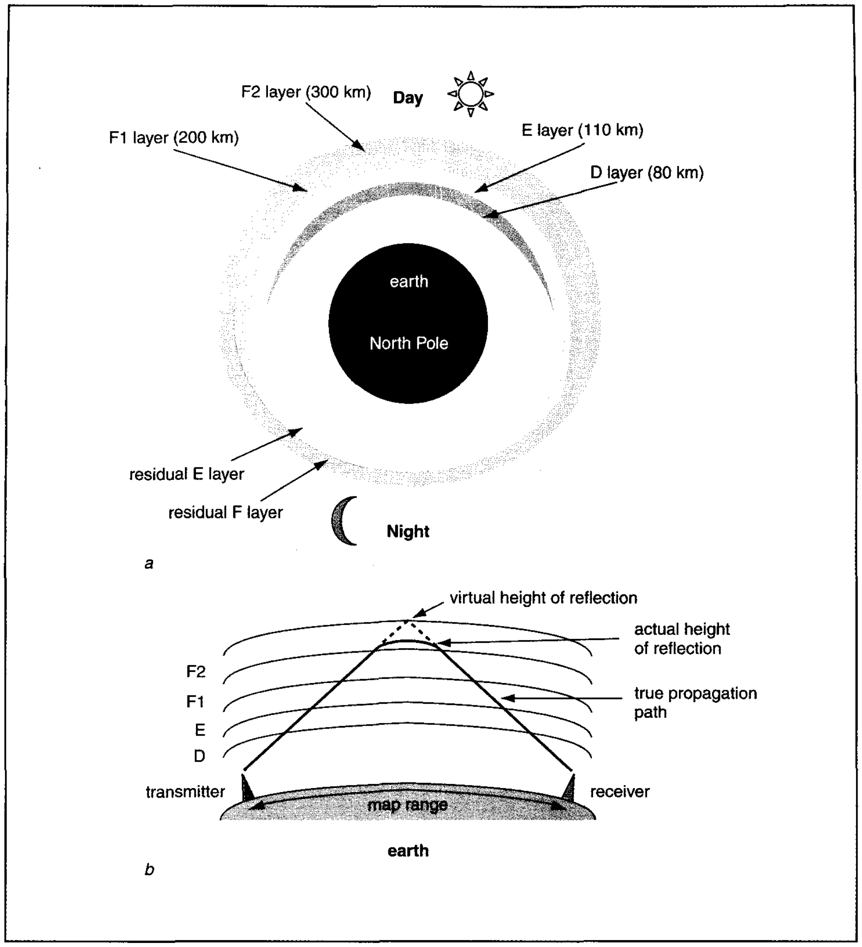



**Fig. 1 (*a*) Ionospheric regions and (*b*) sky-wave propagation via the F2 layer**

spurious emissions into solar space. Grouping the discrete loops leads to the generation of sunspot numbers[2] (SSN), the size and position of which follow an 11-year cycle. Sunspots have been observed since 1610 (detailed results have been taken from about 1874) and have been found to move in an East to West direction across the sun's surface, taking around 13 days to traverse its full width. At the start of a cycle the spots appear at around 30° latitude with respect to the sun's meridian (low sunspot activity). As the cycle progresses the spots increase in number and move toward 15° (high sunspot activity); finally they decline in number and move to latitudes of 5° (back to low sunspot activity and the end of a cycle). When plotted pictorially the number and position of spots gives rise to a 'butterfly diagram' from which the 11-year cycle is evident[2].

In addition to sunspot activity affecting the ionosphere there are also seasonal variations, diurnal shifts and hourly changes in density and height as the earth rotates. With such highly varying characteristics in the basic transmission medium, sky-wave systems do tend to be given second place to other forms of radio communication. Design engineers are often reluctant to employ HF methods and cite low data rate, severe fading, intersymbol interference, high noise levels and poor bit error rate

*NVIS concepts*

Radio waves transmitted in a near vertical (zenithal) direction towards the ionosphere will be returned to the earth's surface given appropriate refraction conditions. The coverage achieved is omnidirectional, terrain independent and can be likened to an 'open umbrella' (see Fig. 2). Employing this technique effectively gives signal coverage in regions which are not (or cannot) be served by conventional LOS systems employing active repeaters. To attain an NVIS effect, adequate radio wave energy must be radiated at angles greater than about 75° or 80° from the horizontal on a frequency that the ionosphere will refract at that location and time[3].

At oblique angles of incidence the ionosphere refracts higher frequency radio waves than with purely vertical irradiation: this is illustrated by the secant equation derived from Snell's refraction law[4]:

$$f = f_v \sec\phi_0 \qquad (2)$$

where $f$ is the radio transmission frequency, $f_v$ is the vertical reflection frequency (overhead ionospheric plasma- or critical frequency) and $\phi_0$ is the angle of incidence between the radio wave and the ionosphere. In the case of vertical irradiation the angle of incidence is zero and $f = f_v = f_C$. This relationship underpins the principle of ionospheric sounding, which is used to measure the D, E, F1 and F2 plasma layers' virtual heights. A sounder can frequency-sweep (or step-pulse) the ionosphere, measure the time taken for an incident wave to return to earth (allowing for retardation in the ionosphere) and produce a frequency ($x$-axis) versus virtual height ($y$-axis) ionogram plot[5]. Ionograms are widely employed by HF radio operators to determine optimum operating frequencies.

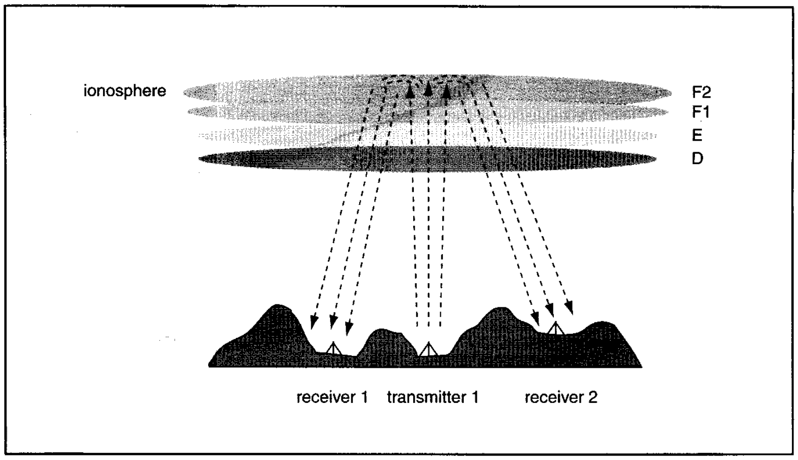
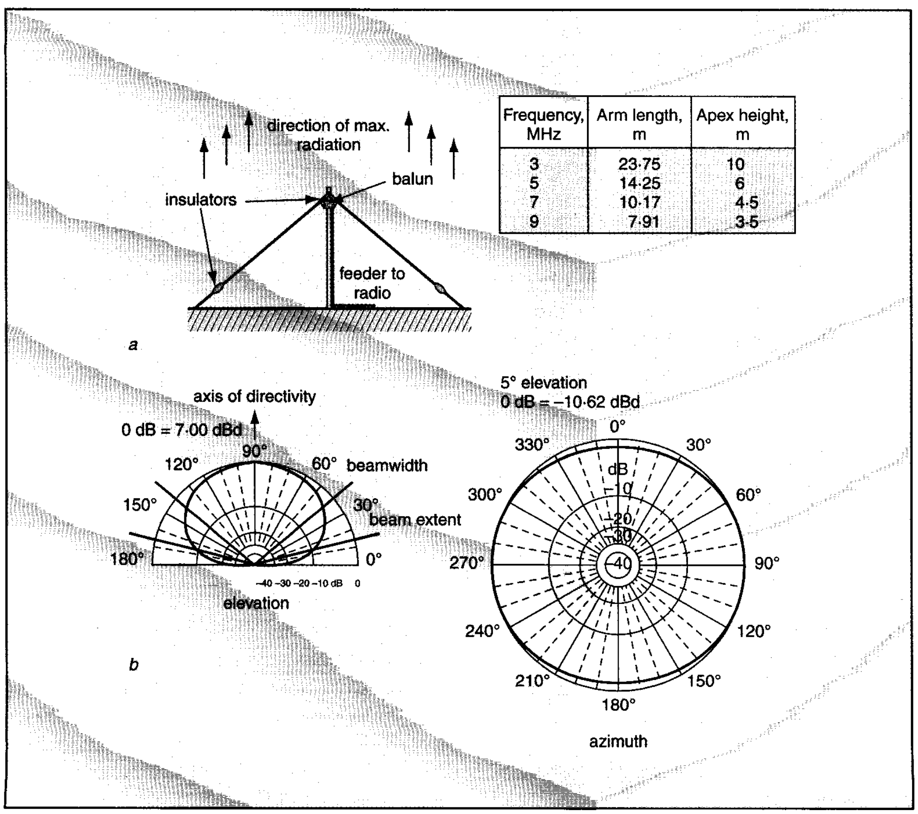



**Fig. 2 Principle behind NVIS HF propagation. Omnidirectional signal coverage with a typical 35–320 km radius is possible**

The best operating frequency for NVIS propagation lies in a 'window' in the lower part of the HF spectrum, generally between 2 and 10 MHz. The width of this window is a function of time of day, season, geomagnetic activity and solar activity (particularly SSN). During periods of increased sunspot activity and enhanced E region ionisation (known as 'sporadic E'), daytime transmission frequencies up to and around 10 MHz can be used. Low sunspot activity (current at the time of writing) restricts operation to 7 MHz and below; winter night-time conditions at low SSN can reduce frequencies to 2 MHz[1]. It is generally accepted that in daytime frequencies in the range 4 to 8 MHz are viable, whilst at night the range 2 to 4 MHz is the norm[6]. In any event, frequencies near the F2 layer's critical value are recommended; frequencies which lie between the E and F2 layers' critical values can cause an NVIS signal to be partially refracted from either layer, resulting in multipath, time delay effects being observed at the receiver[1].

With the advancement in DSP and VLSI devices, sophisticated HF 'adaptable' radios have been developed which utilise built-in sounders to probe the ionospheric path for a suitable transmission frequency (or frequencies) before establishing a communication link. Such radios utilise real-time channel evaluation (RTCE), automatic link establishment (ALE) or real-time frequency management (RTFM) techniques[7,8]; published work has identified military users as the main advocates of such systems[9,10], particularly in the form of base-to-mobile links.




| Frequency, MHz | Arm length, m | Apex height, m |
|---|---|---|
| 3 | 23·75 | 10 |
| 5 | 14·25 | 6 |
| 7 | 10·17 | 4·5 |
| 9 | 7·91 | 3·5 |

**Fig. 3 (*a*) Inverted V antenna suitable for NVIS propagation. The Table gives dimensions for a range of operating frequencies and takes capacitive end effects into account. (*b*) MN radiation plot for an inverted V antenna resonant at 6·8 MHz. The apex height above 'normal' ground (ε = 13 and σ = 5 mS/m) is 6 m.**

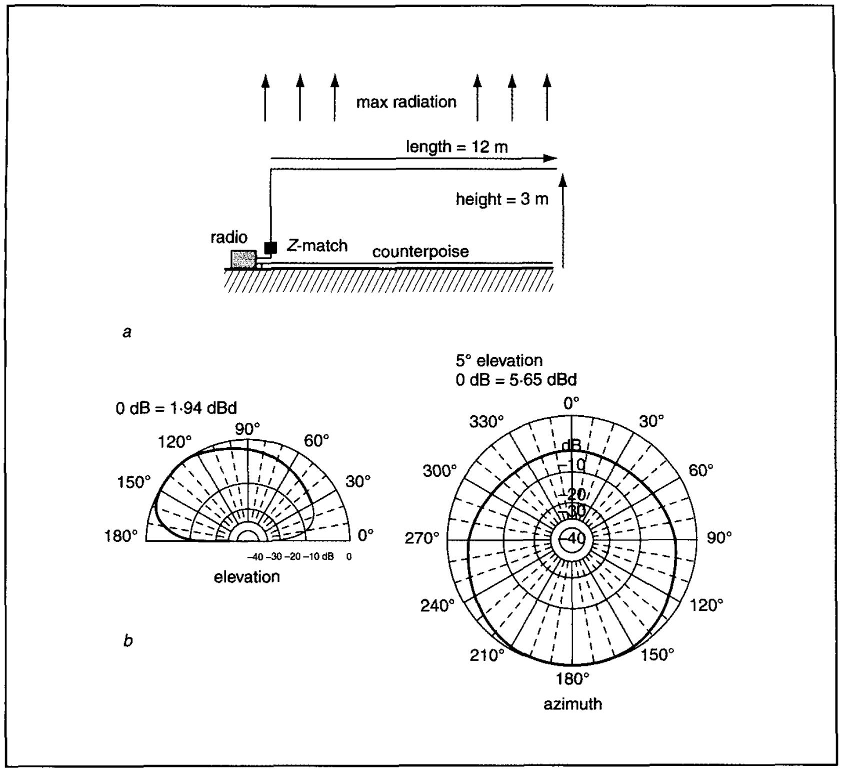



**Fig. 4** **(*a*) 5 MHz 'inverted L' antenna fitted with a wire counterpoise to enhance vertical radiation. (*b*) MN radiation plot for the 5 MHz inverted L antenna. With the dimensions shown, this antenna is ideal for covert deployment and may be adjusted for efficient radiation at any frequency in the 2–10 MHz band using the Z-match LC tuner.**

low level to avoid enemy radar[2]. Conventional LOS propagation has two pitfalls in such a scenario: if the ground is mountainous or built up, signal energy can be blocked or scattered; if the enemy is operating direction- finding (DF) equipment, monitoring can point to the aircraft's location. NVIS techniques can overcome both these problems.

The success of NVIS communication depends critically on the antenna system employed: previous workers have concentrated in this area, principally investigating military applications. For example, at the American Naval Research Laboratory (NRL), 'moment method' numerical electromagnetic code (NEC) software has been used in modelling a 4·8 m tilted whip antenna for use on armoured vehicles at several frequencies over the range 3·5 to 10·5 MHz[14]. Vertical whips, although attractive from a fabrication viewpoint, make very poor NVIS radiators because of their characteristic 'doughnut' horizontal polar pattern and zenithal null. For a whip considered in three positions (i.e. vertical, forward tilt horizontal over the vehicle and trailing tilt horizontal away from the vehicle) it was found that the trailing whip gave the best performance in the zenith direction, but at the expense of large azimuthal gain variations. Proximity analyses (associated with antenna excitation of the vehicle) showed the forward tilted whip to have loss values between 1·4 dB at 7·2 MHz and 3 dB at 3·57 MHz. Losses for the vertical and trailing whip were below 1 dB for the same frequency range.

Other workers have combined the moment method with the powerful, though less well-known, method of 'characteristic modes' in determining the radiation performance of NVIS vehicular antennas[15]. This technique considers a vehicle and its antenna as a single system, then defines a unique set of orthogonal mode currents of varying significance. The far-fields of the mode currents are also orthogonal and can be used in antenna-feed optimisation routines.

Recent published work has described mathematical models of spectral occupancy in central Europe by analysing noise measurements from high- and low-angle antennas[16]. Such algorithms can be advantageous if integrated into the software of adaptive HF radios to give an estimate of the transmitting power required to overcome ambient noise in NVIS links.

*NVIS applications*

It is known that NVIS methods were used during World War II when problems were experienced with VHF and UHF equipment operating in mountainous and jungle terrain. The principle was further pursued during the Vietnam conflict[1,2]. An examination of the loss equation[2] for LOS propagation in wooded and forest regions identifies why HF sky-wave communication appears an attractive alternative: here

$$\text{loss (dB/m)} \approx 0{\cdot}009f\,(\text{MHz}) + 0{\cdot}1 \qquad (3)$$

Taking 60 MHz as an example, the basic loss through 250 m of vegetation is around 160 dB; this VHF channel is virtually unworkable in a base to portable out-station application.

HF radio cannot offer the same throughput as satellite channels (a few hundred bits per second is the norm), but it is cheaper to use and, for NVIS propagation, existing antenna configurations can often be easily altered to achieve vertical radiation. This was evident in the Gulf War when HF supplemented satcom (satellite communication) systems. In particular, NVIS was used for forward military units; effective communication was achieved at ranges from 80 to 240 km[11].

NVIS propagation is beneficial for 'nap of the earth' (NOE) helicopter flying[12,13] when the aircraft remains at

*Proposals for beyond-line-of-sight fixed-site telemetry*

Presently, we are investigating the potential of NVIS propagation for cost-effective telemetry and telecommand HF links operating over short, but non-line-of-sight, paths; the recovery of low-speed, non-critical data derived from remote environmental and biomedical sensors is the main application area. Fundamental radio channel properties such as link availability, transmitter power requirements, fading depth, type and frequency of fading are key elements in the study. The establishment of such a link necessitated a consideration of appropriate hardware, beginning with an examination of suitable antennas.

*Fixed NVIS antennas*

Analysis shows that a practical NVIS antenna must have two primary characteristics: the radiating section must be (i) horizontal and (ii) close to the ground in terms of operating wavelength. Typically, the mounting height should be between $0{\cdot}1\lambda$ and $0{\cdot}25\lambda$.[6] If the antenna is installed outside these limits the vertical gain falls off rapidly. In the main there are three antenna types suitable for zenithal irradiation:

*Balanced wire dipoles:* In their simplest form these are naturally resonant at a single frequency; examples include the horizontal half-wave dipole and the inverted 'V' (see Fig. 3*a*). The latter is attractive for portable deployment since it requires only a single central support; care must be taken to ensure the apex angle of the 'V' is not less than 120°.

The polar pattern of an inverted 'V' cut for 6·8 MHz operation and mounted approximately 6·0 m above ground level is shown in Fig. 3*b*. This plot was obtained using MN software[17]. The antenna's main axis of directivity and normal −3 dB beamwidth, which effectively set the final geographic coverage, are readily identified. The beam extent is identified by the −10 dB response points, and is often specified in NVIS systems since it gives an indication of the amount of energy which may be radiated horizontally (in transmit mode), or how much interference may come from ground waves and man-made noise sources (when receiving). The plot shown has a beamwidth of around 100°, with a rapid fall-off in response to the 150° beam extent. The azimuth view shows that omnidirectional coverage is achieved, giving the final umbrella propagation effect previously discussed. A simple inverted 'V' has a bandwidth (defined between the 2·0 VSWR — voltage standing wave ratio — points) of about 5 % of its resonant frequency and at low elevations presents a feed resistance close to 50 Ω.

Changing the operational frequency of these antennas is a matter of physically altering their length, as illustrated by the Table in Fig. 3*a*. In restricted spaces, loading inductors may be added to each arm to give electrical lengthening or parallel-resonant 'traps' can be inserted to give resonance at a number of discrete frequencies[18].

Variations of the basic dipole do exist. These include the Shirley dipole, the Jamaica antenna and the Fan dipole[19,20]; all incorporate modifications to enhance bandwidth and/or vertical gain.

*Unbalanced wire antennas:* Unbalanced antennas include the inverted L and random-length wire. An unbalanced radiator uses the ground below as its electrical image. The

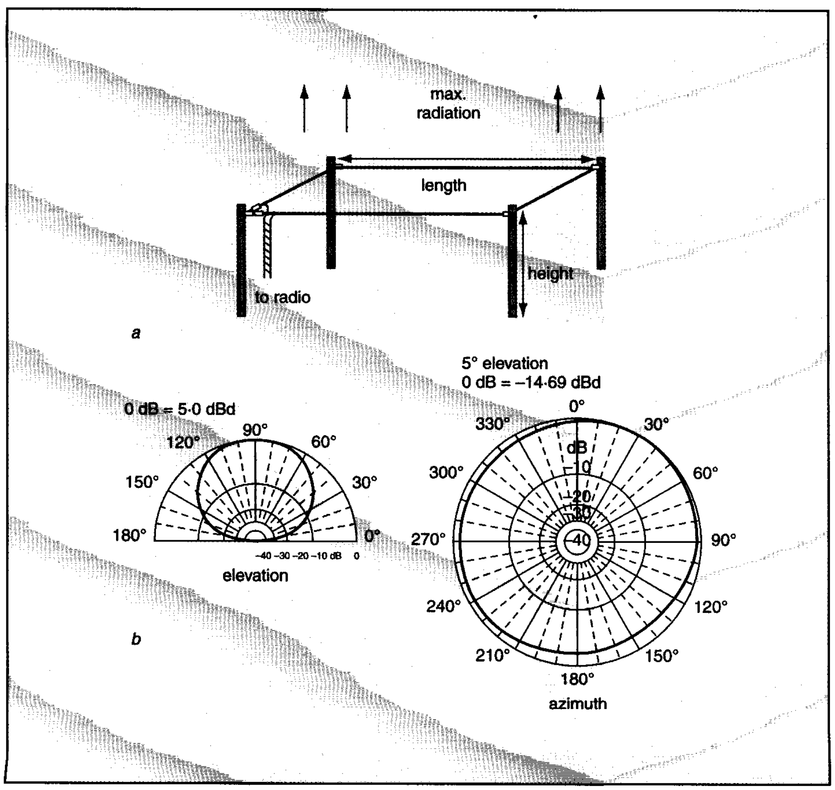



**Fig. 5 (*a*) A full-wave loop antenna; each side is λ/4 in length and the height should be in the range 0·15–0·25λ. A 4:1 balun is needed for low-impedance coaxial feed. (*b*) MN radiation pattern for a full-wave 6·8 MHz loop mounted 0·25λ above normal ground**

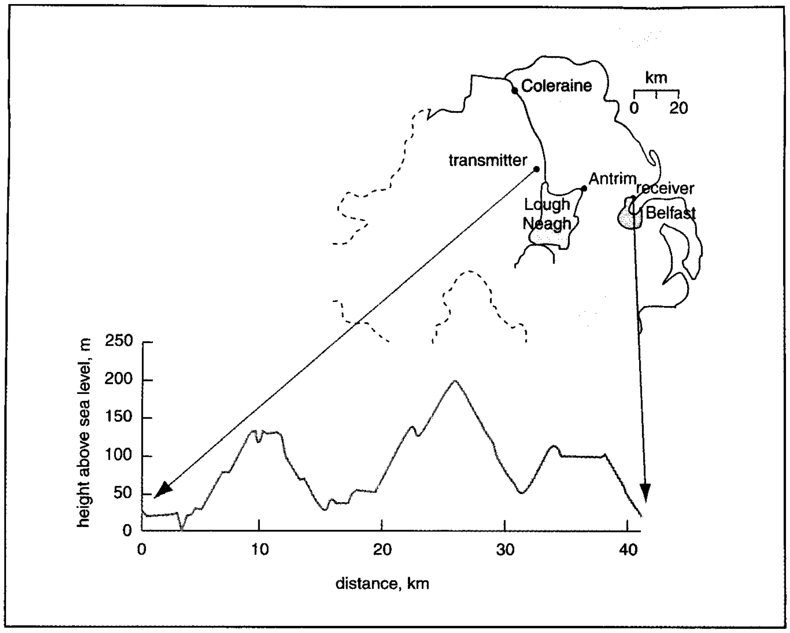



**Fig. 6 Ground profile between the NVIS test link transmitter and receiver sites**

slanted by 14° so that the remote end is 0·1 m from the ground. Like the inverted 'V', this antenna is ideally suited to temporary out-station deployment.

*Wire loop antennas:* Full-wave loops are a popular design choice for antenna engineers, over a wide range of frequencies and for many applications. The HF band is no exception; antennas such as the 'Patterson loop' perform well[21], though their physical size does become unwieldy. Detuning can be caused by interaction with nearby conductive objects and good efficiency necessitates proper layout; loops are also time-consuming to build. Fig. 5*a* illustrates a typical example.

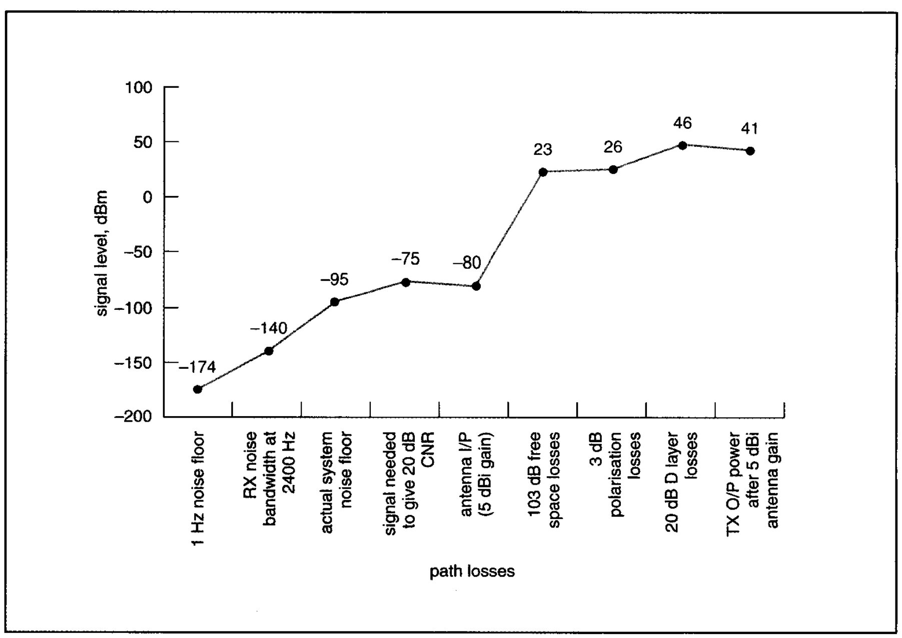
Electrically, a loop is capable of excellent performance as a zenithal radiator: an MN plot for a 6·8 MHz example is given in Fig. 5*b*. Compared with the inverted 'V', the beamwidth for the full-wave loop is about 80° and the beam extent is 135°, giving a narrow vertical polar response. Given its constructional requirements and enhanced vertical propagation properties, a loop is ideally suited for permanent base station use.

entire length of such an antenna radiates, from the connection point on the radio to the end of the wire. If the ground beneath the antenna is not very conductive a counterpoise wire has to be provided to improve vertical radiation, as illustrated in Fig. 4*a*; here a horizontal section of 12 m and a vertical section of 3 m are used as an example, giving a wire antenna with quarter-wave resonance at 5 MHz. The polar plot of Fig. 4*b* shows a main lobe emanating from the rear of the antenna (at around 135°) with a slightly reduced vertical gain; the field of the vertical antenna segment is interacting with that of the horizontal segment to cause this. MN modelling indicates an increase of 1·25 dB in vertical gain if the 12 m horizontal section is

## 3 An NVIS test link

A 6793 kHz NVIS simplex link between the University of Ulster's Jordanstown campus (the monitoring site) and an out-station 42 km distant (the transmitter site) has been operational since February 1998. The ground profile

**Fig. 7 Simplified power level chart for the oblique sounder, allowing calculation of the transmitter output power**



between the locations is illustrated in Fig. 6. With no LOS path only a residual surface wave component reaches the receive antenna. Full-size, balun-fed inverted 'V' antennas are used at each end of the link, both mounted 6 m above ground level.

The basic path attenuation encountered[19] is around 110 dB of 'free space' propagation loss, plus 10–20 dB ionospheric losses. To determine the transmitter output level required for a nominal 20 dB carrier-to-noise ratio (CNR) at the receiver, a basic power level chart (neglecting seasonal and day/night variations) may be constructed, as shown in Fig. 7. A minimum of 12·6 W is required for a workable channel under 'normal' ionospheric conditions.

In our case the transmitter (a computer-controlled ICOM IC-706) develops a constant 20 W average power into 50 Ω. A JRC NRD 515 receiver fitted with a 300 Hz IF filter and switched to CW mode is used for signal strength monitoring, using its fast AGC line as the output point.

Channel monitoring takes place in 24-hour blocks, once per week. For identification purposes the transmitted signal incorporates a 5 second, two-tone header. At the monitoring site, two-tone detection is achieved at baseband using the low-pass filtered and ANDed output of two NE567 decoders. A software algorithm fed by the tone decoding circuitry makes a decision on the legitimacy of the received ID using a 50% timing threshold and, if successful, initiates signal level logging of a single-tone transmitted for 30 s after the header. This process is repeated every 5 minutes.

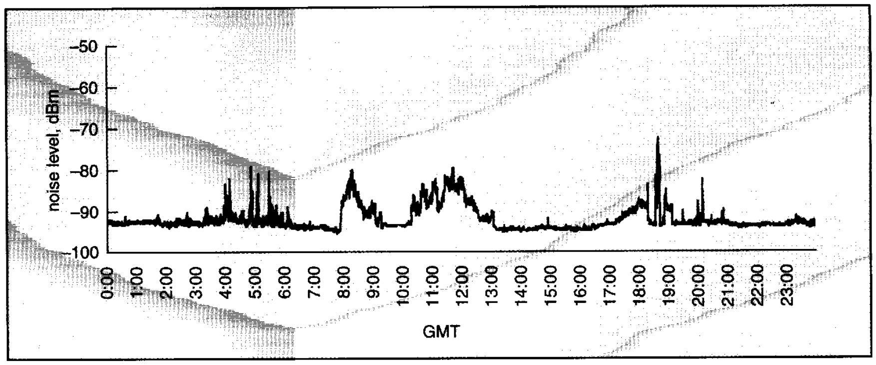



**Fig. 8 6793 kHz interference levels measured over a 24 hour period, in a 2·4 kHz receiver bandwidth**

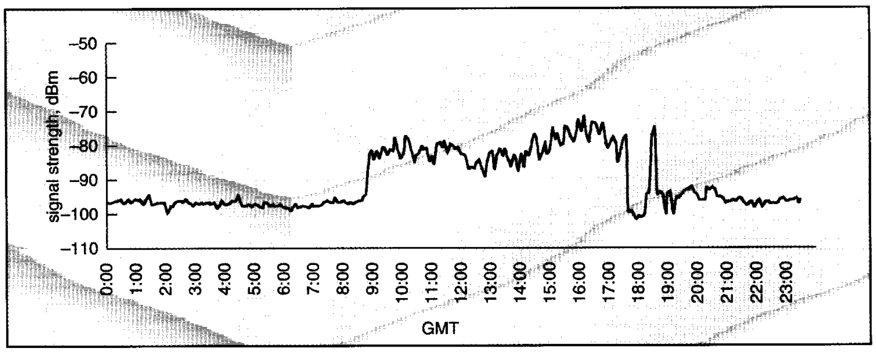



**Fig. 9 NVIS channel opening at 6793 kHz, over a 42 km path — February 1998**

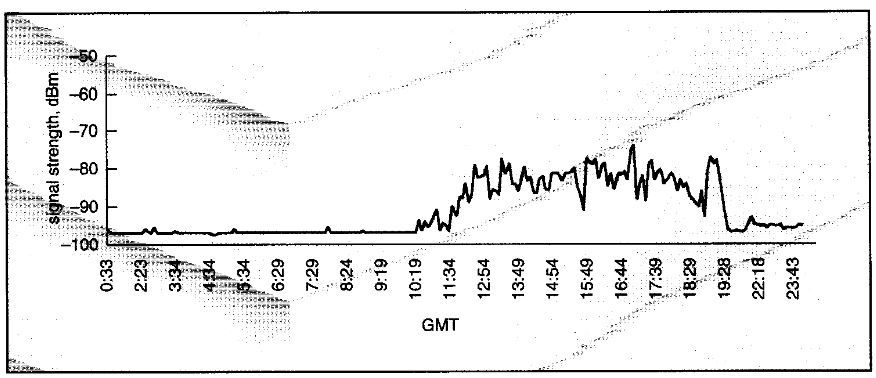



**Fig. 10 NVIS channel opening — May 1998**

*Channel characterisation*

To determine when periods of severe signal interference might be expected at 6793 kHz, the base receiver's input levels were assessed for 24 hours, on this occasion in an IF bandwidth of 2·4 kHz. For this investigation, conducted late in 1997, the AGC-line was monitored continuously at 4 samples/s; the observations are presented in Fig. 8. Unwanted signals are most evident from 08:00 to 12:30 and from 18:00 to 19:30 GMT. The first period suggests that daytime HF communication traffic from Europe and countries further East is problematic: the ionosphere is well formed in these regions several hours in advance of the UK. Around local mid-day, with the ionosphere overhead receiving maximum radiation, increased D region absorption helps to attenuate distant HF noise and interference.

The period around 18:00 is just after the local day–night transition, when the D layer disappears: noise levels rise briefly, originating at longitudes East of the UK where a residual F layer persists for a short time. After 19:00 the channel quietens, and sustains a low background level

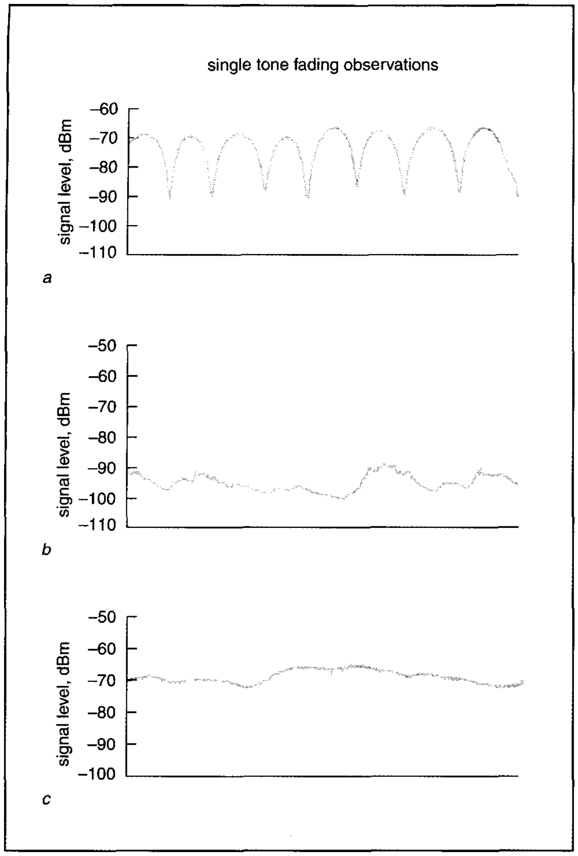



**Fig. 11 Observations on 10 s portions of carrier, illustrating the types of fading found under NVIS propagation conditions: (*a*) fast interference, or flutter; (*b*) mild interference; (*c*) steady channel with minimal fading**

throughout the night. The geographical location of the UK and the noise observations made would suggest that little, if any, interference might be expected from the West. Europe and Far Eastern countries appear to be the main source of interference on an NVIS link. Daytime communication traffic emanating from Europe and the Far East is always going to be present, especially in the morning hours.

Impulsive 'static' noise from distant (near equatorial) thunderstorms also has a part to play, but to a lesser extent. Monitoring the receiver's audio output revealed modulated transmissions as the main interference source.

*NVIS channel 'open time'*

At the time of writing the SSN is low (moving out of the dip of Cycle 22) so current observations pertain to a near-worst case scenario for NVIS channels, dependent as they are on sustained solar UV generation at moderate levels.

Fig. 9 illustrates the availability, or 'open time', of the test channel during a 24-hour period in early February 1998. The plot, obtained from measuring the received single tone, represents the average value of signal-strength data logged every 5 minutes. NVIS propagation is not truly established until 09:00, three to four hours after sunrise. Before 09:00 the ionisation level is so low that refraction cannot take place and the transmitted wave passes through the ionosphere. However, once a suitable ionisation level is reached the channel opens, after which time communication traffic (telemetry or otherwise) could be supported until well after dusk. Plots for frequencies other than 6793 kHz will produce different results; higher frequencies, not exceeding the F layer's critical value, would open later, whereas lower frequencies would open earlier. For digital transmission, frequencies close to the E layer's critical value should be avoided to minimise multipath effects caused by partial E–F layer refraction. An interesting point to note is the speed with which the ionosphere becomes ionised; the sky-wave path was established within a 10 minute period. This was a feature reflected throughout the winter observations, suggesting that a cold ionosphere responds quickly to UV radiation from the sun.

A similar test conducted in May gave the result shown in Fig. 10. The channel's open period is comparatively the same with a noticeable shift in time. Going forward into summer the sun's relative position is changing daily and longer excitation of the ionosphere can be expected; the average received signal strength is reduced by about 6 dB, compared to February's observations. This is attributed to greater D region signal absorption (due to the prolonged ionospheric excitation) and reduced F layer critical frequencies. During low solar activity, winter F layer critical values exceed those for summer. Observations on a single frequency, suitable for F layer NVIS propagation throughout the year, will show less signal loss during winter. In any event, May's signal is well above the receiver noise floor and the channel could support communications during the opening without the need for a frequency change. The opening transition is slower than for the previous test: approximately 30 minutes is needed for channel establishment. Once again, this became a feature as summer progressed.

*Channel fading*

A characteristic of all sky-wave channels is the presence of fades in the received signal, and short-haul NVIS paths are no exception. HF fading can be classified into several types, principally multipath, interference and Faraday[2]. A close examination of three separate 10 s portions of received carrier (Fig. 11) for February's observations identify the types of fading commonly found on our test link. Fig. 11*a* is a classic example of fast interference fading (a rate of around 48 per minute), otherwise known as 'flutter' fading. Interference fading is caused by ionospheric surface irregularities, mainly attributed to clouds of electron enhancements or depletions which drift with neutral winds. In Fig. 11*b* the fading is random in nature with no specific pattern: it is still classed as mild-interference in type and results from the incident wave passing through (and being refracted by) inhomogeneous ionospheric regions. Interference fading is generally variable throughout the total channel opening. Fig. 11*c* illustrates a channel with minimal fading, representing ideal conditions for digital data transmission.

A frequency analysis of all the signals received during the openings recorded in February and May resulted in the

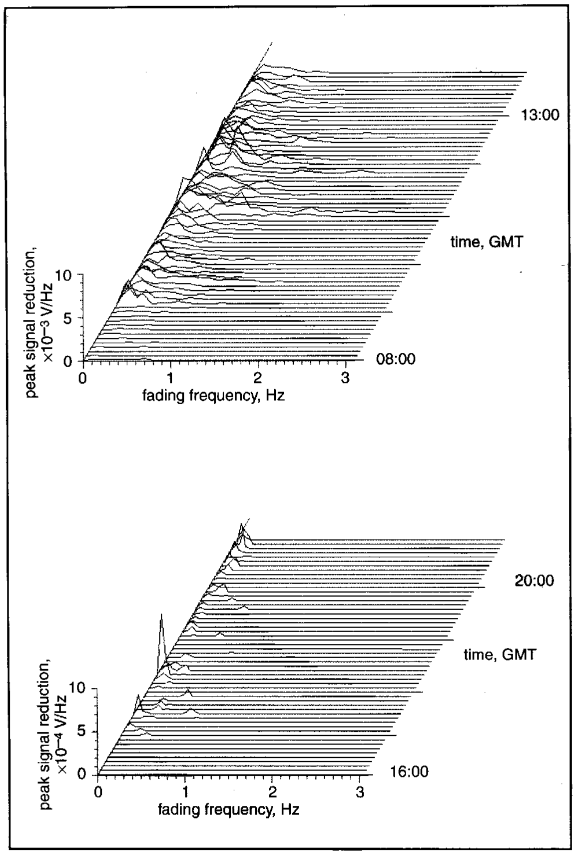



**Fig. 12 Fading frequencies for the February 1998 observation**

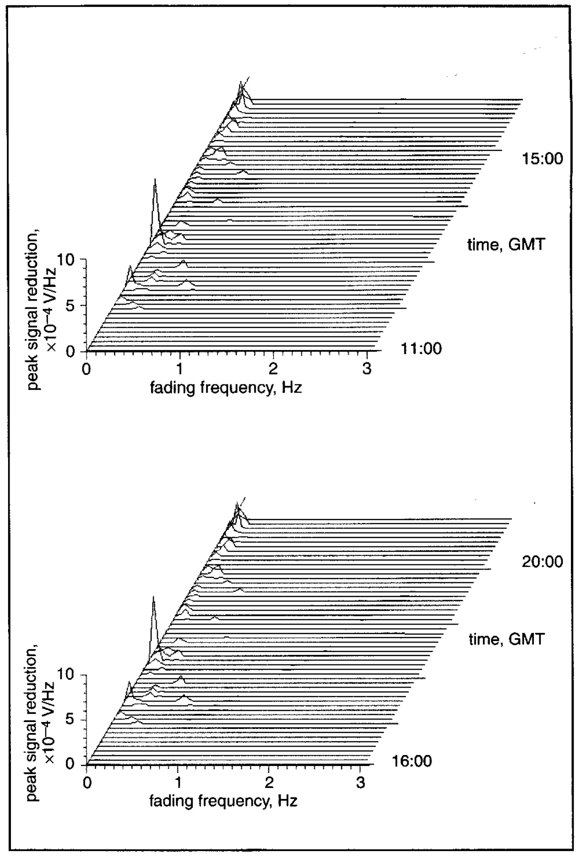



**Fig. 13 Fading frequency profile for May 1998**

plots of Figs. 12 and 13, respectively; these illustrate the amount and frequency of fading observed. The plots were obtained by deliberately over-sampling the JRC receiver's AGC line at 100 Hz, using a 30 Hz anti-aliasing pre-filter (in the absence of relevant information the latter's cut-off frequency was selected following a review of published flutter rates[2,4,5] on a range of non-NVIS links). After sampling, the raw AGC values were converted to equivalent receiver input voltages. Before finally passing the samples through a discrete Fourier transform all DC components were removed, data window DC correction was applied[22] and a Welch window function used to remove edge effects. An indication of the fading depth may be obtained from the 'peak signal reduction' axes in each Figure. Note that the values shown represent the accumulated decrease in signal voltage at specific frequencies and are not instantaneous receiver input levels.

In Fig. 12 the channel opens sharply at around 09:00 and fading is present in some form for the whole opening. For two to three hours either side of noon only low-frequency, shallow fades are evident, giving reasonably good channel conditions. After 14:00 the fading depth increases and more high-frequency components appear (the latter indicative of flutter fading). As the channel draws to a close the ionosphere appears highly turbulent as it loses the ionisation built up during the day; fast fading increases, superimposed on a deepening low-frequency component. Data transfer would now be a problem as the received signal is dropping out more frequently and for longer periods.

Subjecting the May observations to the same data manipulation resulted in the plot of Fig. 13. The channel mainly displays the characteristics of low-frequency fading at greatly reduced amplitudes (note the times-ten magnification factor of the *y* axis, compared to Fig. 12). Flutter fading is virtually absent throughout the opening, yielding a high-quality channel. Once again as the opening draws to a close the ionosphere displays some turbulent characteristics, but with a much reduced effect compared to the winter observations.

## 4 Discussion

In this paper we have reviewed the principles of, and basic hardware requirements for, NVIS HF radio transmission. In addition to normal voice and data traffic, practical assessments indicate its strong potential as a low-cost method of telemetering non-critical data over difficult terrain, with service ranges extending to several hundred kilometres. Even a single-frequency, voice-bandwidth channel will provide a good-quality propagation window at some time during any 24 hour period, allowing a 'store and forward' scheme to be implemented around a real-time

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channel evaluation (RTCE) protocol[23].

Once established, the NVIS channel is not ideal: in particular, daytime transmission frequencies well below the F layer's critical value are subject to higher fading in terms of depth and frequency. During low solar activity the critical frequency in winter is higher than that in summer. Because of increased D layer absorption in summer, path losses are higher than in winter.

To ensure full 24-hour operational NVIS capability, frequency agility will invariably be required; this detracts from the simplicity of the scheme as proposed and has hardware implications in cost-sensitive situations, especially if automatic antenna tuning must be implemented. Continued investigation, with half-duplex sounding effected on a full-time basis, is warranted to further characterise seasonal and diurnal channel variability as the next sunspot cycle proceeds.

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