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New sounding modes for SuperDARN HF radars

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Abstract: We have developed several new sounding modes for SuperDARN HF radars to increase operation flexibility ("Nasu" mode, etc.) as well as to obtain both higher time resolution special camping beams data and global convection patterns simultaneously ("Basyouhu" mode). Utilizing the new "Basyouhu" mode, we were able to detect, for the first time, very rapidly moving transient phenomena (about 20 km/s) passing through the SuperDARN radar's field of view without any ambiguity or uncertainty.

1. Introduction

The Super Dual Auroral Radar Network (SuperDARN) HF radar system (Greenwald *et al.,* 1995) was originally developed at Johns Hopkins University Applied Physics Laboratory (Greenwald *et al.,* 1985) and has become a powerful tool for measuring the ionospheric plasma drift velocity with a high temporal and a high spatial resolution. SuperDARN has a very large field of view that covers most of both the southern and northern high latitude ionospheres. The system enables small-scale structures in the ionosphere as well as global ionospheric convection patterns to be investigated as snapshots.

Over the last decade, progressively sophisticated sounding modes have been developed by several groups in the SuperDARN community to achieve their scientific goals more effectively.

The SENSU (which stands for "Syowa South and East HF Radars of NIPR for SuperDARN" and also means "fan" in Japanese, describing the shape of the SuperDARN radar's field of view (FOV)) Syowa South and Syowa East radars are located at Syowa Station, Antarctica (69.0°S, 39.6°E); the boresites are 159.0 degrees and 106.5 degrees, respectively (measured clockwise from geographical north). Figure 1 shows the FOVs of the SENSU radars. At Syowa Station, the magnetic local time (MLT) is almost the same as the universal time (UT). The Syowa East radar's FOV covers a large MLT range, up to a few hours earlier than the Syowa MLT range.

We have developed several new sounding modes, such as "Nasu" and "Basyouhu" modes, using SENSU Syowa radars to attain a higher time resolution ionospheric backscatter data for both special camping beams and global scans to study transient ionospheric phenomena as well as pulsation phenomena in detail. These new sounding modes also enable the HF radars to be operated more flexibly.

We herein describe our new radar control programs, sounding modes and our initial results.

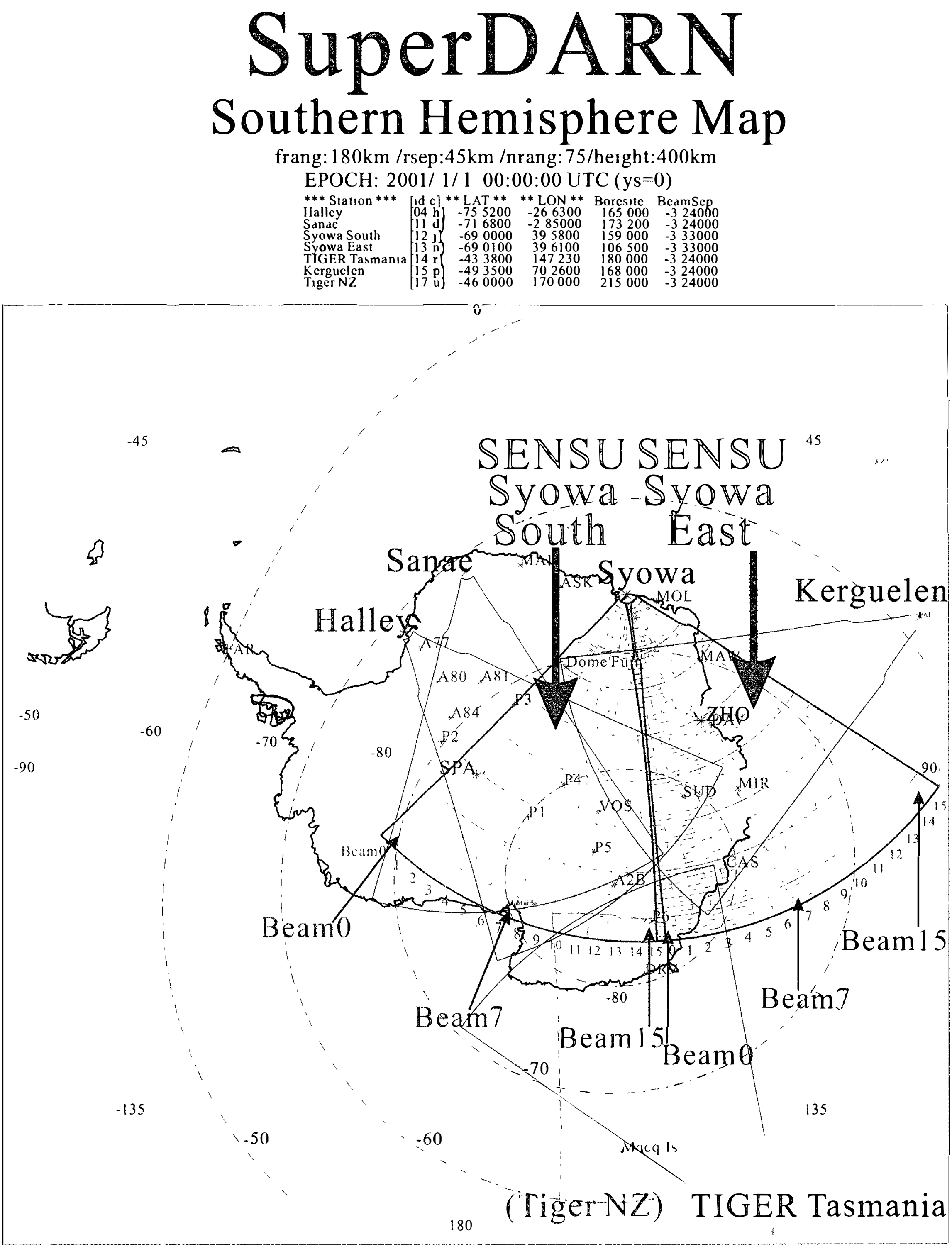

Fig. 1. *Fields of view (FOVs) of the SENSU radars in the southern hemisphere SuperDARN map. The locations of the beams are indicated. At Syowa Station, the magnetic local time (MLT) is almost the same as the universal time (UT). The Syowa East radar FOV covers a large MLT range that extends up to a few hours earlier than the Syowa MLT.*

2. Radar operating system and development of new sounding modes

The radar operating system that has been developed at JHU/APL can control the radar hardware in a flexible manner, process received signals, and produce fitted physical data (echo power, line of sight plasma Doppler velocity and spectral width, etc.) in real time (Greenwald *et al.,* 1985; Baker *et al.,* 1988).

The original version of the radar operating system was a group of software that ran on a Data General MP200 microcomputer. After that, the radar operating system (called RADOPS) was improved and migrated to a real-time operating system, QNX OS, on two IBM compatible Intel i386 and i286 based PCs. The new system was called RADOPS/386 (later changed to RADOPS/486 after its platform was upgraded to an i486 based PC).

The RADOPS/386 system included an "interpreter" that can interpret the radar operation language program, called RADLANG, by which radar operators can change the basic radar operation parameters, such as the pulse pattern, pulse length, integration time, transmitted frequency, beam sequence, and so on, enabling greater operational flexibility. A schedule program, developed by the University of Leicester, radar was also implemented in the RADOPS/386 system. This schedule program allows the sounding modes (*i.e.* the RADLANG programs) to be changed according to a given schedule. The "interpreter" enabled most of the radar operation parameters to be changed, but these changes were limited by the interpreter/RADLANG implementation. The addition of new variable parameters to the interpreter/RADLANG system was also difficult.

Radops2000 was developed by the JHU/APL group. It does not require "RADLANG interpreter" any more. Instead, each program for each radar operating mode is written in pure C language, enabling greater flexibility. Each radar operating program is called a "radar control program" ("RCP").

Recently, an even newer radar operation and analysis system, called "Radar Software Toolkit" ("RST") OS, has been developed by JHU/APL. RST OS combines the real-time radar operating system with off-line data analysis software using the same source tree. This allows the radar operation and analysis software to be maintained coherently and consistently and also enables the radars to be operated more flexibly. The radar operating system code used in RST OS was written from scratch, and the library functions (APIs) are different from those in the older Radops2000. We have migrated our special RCPs for Radops2000 to the newest RST system. Below, we describe the "Nasu" radar control program for Radops2000 and the "Basyouhu" program for the RST OS, as well as the basic "normal_scan" mode.

2.1. *normal_scan*

The "normal_scan" mode was developed at JHU/APL as a basic sounding mode to be run during SuperDARN "Common Time" days. The pulse length is 300 microseconds, producing a range separation (range gate) of 45 km. The first range is located 180 km away from the radar. The pulse pattern is fixed at an unequally spaced seven-pulse one to determine multiple lags of the autocorrelation functions. The basic lag separation is 2400 microseconds. The transmitted frequency can be varied between 8 and 20 MHz. A simple beam sequence, such as

bs0-1) *0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15*
(start_beam = 0 and end_beam = 15)

or

bs0-2) *15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0*
(start_beam = 15 and end_beam = 0),

is used, and the integration time for each beam observation is 7 seconds long. After each beam sequence, this mode waits for the next 2-minute boundary by reading the GPS clock before starting the next scan to synchronize all the SuperDARN radar observations, enabling a global convection pattern to be produced every two minutes. For special observations, a few command line arguments can be used to change a limited number of operational parameters. The main variables that can be changed are the integration time, first range, range separation, and the Tx frequency during daytime or the night-time. The start_beam and end_beam parameters can also be changed, but special beam sequence arrangements cannot be used.

2.2. *"Nasu" scan*

We have developed a new sounding mode, that we have called "Nasu", which means "to accomplish" (or "aubergine" that the first author likes) in Japanese. The Nasu mode is based on the "normal_scan" mode described above and enables the radar hardware to be controlled with maximum flexibility while providing a high level of time resolution for the special camping beam data. These features are especially useful for the study of transient phenomena in the ionosphere.

Most radar operating parameters can be changed and specified very easily using the "Nasu" RCP and its several command line parameters. Any number of special camping beams can also be specified to simultaneously observe the specified beams at very high time resolutions, in addition to the normal global scans. For example, if we specify 2 special camping beams, S1 and S2, and set the beam step number to 2, the beam sequence is as follows:

bs1) *0 S1 2 S2 4 S1 6 S2 8 S1 10 S2 12 S1 14 S2.*

In this situation, data from beams S1 and S2 can be obtained at a time resolution of about 4 times the beam integration time. The global convection pattern can be observed at the same time resolution as that of normal_scan if the integration time is the same as the normal_scan mode. Frequency scans can also be performed. In this case, the transmitted frequency is changed for every beam scan; in this manner, a large amount of echo can be obtained from different parts of the echo region because of the difference in ray paths between the transmitted frequencies.

Using the Nasu mode, most of the basic operational parameters can be adjusted to suit the requirements of the experiment. However, the number of available beam sequences is relatively limited. Therefore, this mode is suitable mainly for high time resolution special camping beam observations and various test operations, such as frequency scan.

2.3. "Basyouhu" scan

The Nasu mode enables high time resolution special camping beam data and global convection data to be obtained simultaneously. However, the global convection full scan data is not fully optimized (the data obtained is about the same as that received by normal_scan), and the temporal resolution is sometimes low. To obtain both high time resolution special camping beam data and high time resolution global scan data, a more complicated beam sequence is required.

Various new modes, named "Basyouhu", have been developed to observe special camping beam(s) with a high time resolution while simultaneously optimizing the global scan to obtain the highest possible time resolution. The name "Basyouhu" was selected to describe the complexity of the beam sequence, which we feel is similar to the very fine structured traditional textile "Basyouhu" that is made in Okinawa region of Japan.

To construct a Basyouhu scan, we first start with the simplest Common Time "normal_scan" mode. In other words, if the starting beam is 0 and the ending beam is 15, the beam sequence of the normal_scan is as follows:

bs2-0) *0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15.*

Two special camping beams (A and B) are inserted between the normal scan beams:

bs2-1) *0 A 1 B 2 A 3 B 4 A 5 B 6 A 7 B 8 A 9 B 10 A 11 B 12 A 13 B 14 A 15 B.*

Each of the special beams (A and B) can then be observed with a time resolution of 4 times the beam integration time, while data on the global convection pattern can be obtained at a time resolution of 32 times the beam integration time, *i.e.* twice the resolution of a single beam scan, if the beam integration time is the same as the normal _scan, which is usually 7 s. If we adopt a 3-s integration time, as we usually do for the Basyouhu scan, data from each special camping beam can be obtained about every 12 s, while global convection pattern data can be obtained about once every (slightly less than) 100 s (not exactly 96 s due to a small amount of overhead in RADOPS) (if GPS time synchronization is not performed).

Next, the beam sequence of the normal_scan is reordered so that the even-numbered beams are first and the odd-numbered beams are last:

bs2-2) *0 2 4 6 8 10 12 14 1 3 5 7 9 11 13 15.*

With this beam sequence, the time resolution of the global scan is twice that obtained with a normal_scan, although the spatial resolution is half if the scan is split into 2 fast scans. If the entire beam sequence is regarded as one scan, however, we can obtain the same temporal and spatial resolution data as that of a normal_scan.

We next reorder the even-numbered and the odd-numbered parts of the scan into two sections as follows:

bs2-3) 0 4 8 12 2 6 10 14 1 5 9 13 3 7 11 15.

Using this sequence, we can obtain global scan data that is four times higher than that of a normal_scan, though the spatial resolution is one-fourth that of the normal_scan. If the entire sequence is regarded as one scan, we can obtain the same temporal and spatial resolution as that of a normal_scan; moreover, we can also regard this as a combination of an even-numbered beam scan and an odd-numbered beam scan, enabling the same data analysis as that used in the beam sequence bs2-2 above to be performed as well.

If we wish to observe one or more selected beams with a very high time resolution while obtaining global scan data, special camping beams are set between the global scan beams in the beam sequence, as shown in bs2-1 above.

For example, if beams 2, 5 and 8 are selected as special camping beams, the beam sequence is as follows:

bs2-4) *0, 5, 4, 8, 8, 2, 12, 5, 2, 8, 6, 2, 10, 5, 14, 8, 1, 2, 5, 5, 9, 8, 13, 2, 3, 5, 7, 8, 11, 2, 15, 5, ……*
(G 0, 4, 8, 12, 2, 6, 10, 14, 1, 5, 9, 13, 3, 7, 11, 15, ……)
(S 5, 8, 2, 5, 8, 2, 5, 8, 2, 5, 8, 2, 5, 8, 2, 5, ……)

(G stands for global scan beams, S for special camping beams).

In this sequence, beams 2, 5 and 8 are included in both the special beams and the global scan beams. If the sounding parameters for the global and special beams are completely the same, as is usually the case, beams 2, 5 and 8 can be skipped in the global beam sequence; instead, part of the special camping beam sequence is also treated as part of the global beam sequence. Thus, we can also increase the time resolution of the global scan. After dropping the last beam 15 in the global scan to reduce the time required for the scan, we obtain the final Basyouhu beam sequence:

bs2-5) *0, 5, 4, 8, 12, 2, 6, 5, 10, 8, 14, 2, 1, 5, 9, 8, 13, 2, 3, 5, 7, 8, 11, 2,*
(G 0, 4, 8, 12, 2, 6, 10, 14, 1, 5, 9, 13, 3, 7, 11,)
(S 5, 8, 2, 5, 8, 2, 5, 8, 2, 5, 8, 2,).

Each of the special camping beams (2, 5 and 8) can then be observed with a time resolution of 6 times the beam integration time (or (number of special camping beams) * 2 times the beam integration time), while the global convection pattern can be simultaneously obtained at a time resolution of 24 times the beam integration time, *i.e.* 1.5 times the time resolution of a normal_scan period if the beam integration time is the same as that of a normal_scan. For the Basyouhu scan, we normally use a 3-s integration time, which is less than half the normal_scan integration time (7 s). Thus, special beam data can be obtained approximately every 12 s and global scan data once every 72 s (actually, the time resolution is not exactly 72 s but slightly larger because of RADOPS overhead).

Although the spatial resolution is reduced by one-fourth, the time resolution of the global scan data is 4 times higher (about every 20 s) than that obtained using the normal _scan mode. If a very rapid, transient phenomenon passes through the radar field of view, the global scan can be split into 4 parts to determine the movement of the phenomenon (*i.e.* the velocity of a plasma bulk flow and its time evolution) much more precisely.

The selection of special camping beams and the construction of the Basyouhu scan vary according to the scientific aim of the experiment. To detect Pc3 pulsation, only one special camping beam with an integration time of 2 or 3 s is used. To detect fast flow signatures around the cusp region, 2 or 3 special camping beams positioned relatively close to each other are selected to detect the cusp region of any interplanetary magnetic field (IMF) Bz condition and also to detect temporal and spatial variations in small-scale transient phenomena. The selection of special camping beams thus depends on the type of observation being performed. When attempting to synchronize the observations with those of a satellite, the pre-calculated geomagnetic footprints of the satellite are selected as the special beams and other radar special beams are used to cover the cusp latitudes.

3. Initial results and discussion

Here, we present our initial observation results using the Basyouhu sounding mode.

Figure 2 shows the SuperDARN SENSU Syowa East radar range-time-parameter plot for beam 7 over a period from 0900 to 1000 UT on July 11, 2000. The upper panel shows the backscatter echo power in dB, the middle panel shows the line-of-sight (LOS) Doppler velocity in m/s (positive values imply plasma drift toward the radar and

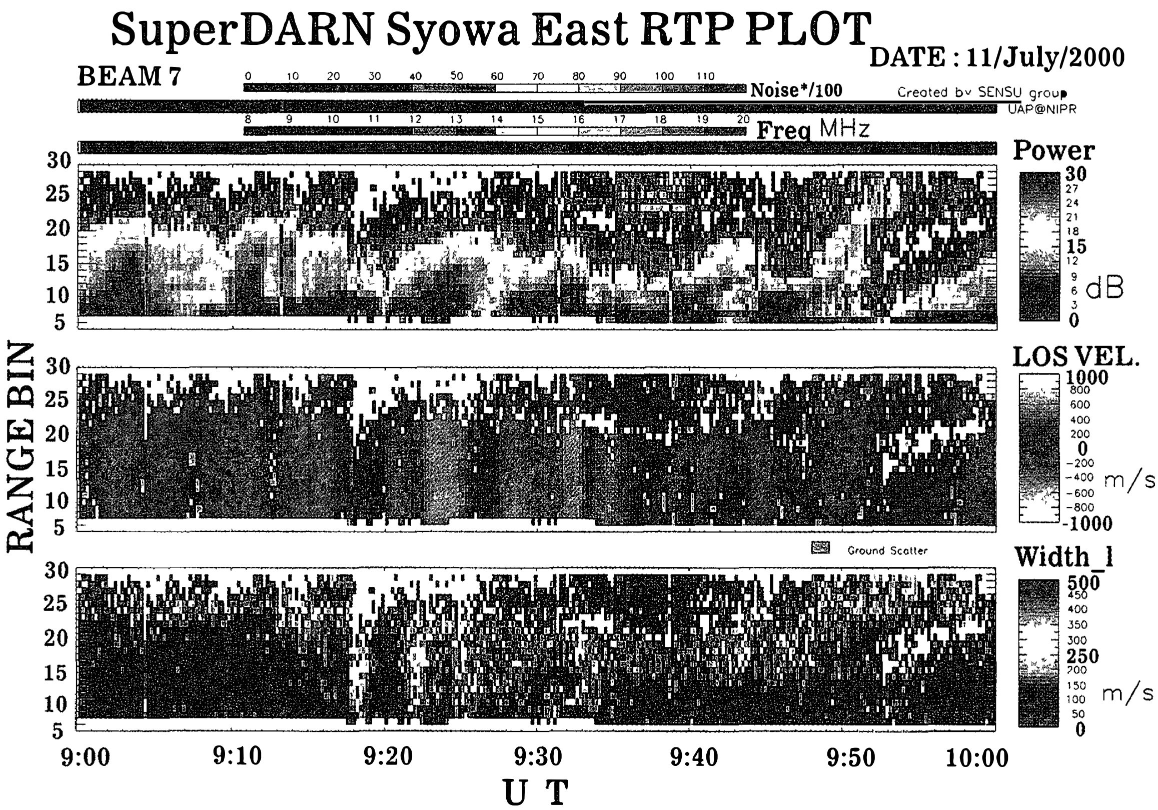

Fig. 2. SuperDARN Syowa East SENSU radar range-time-parameter plot for beam 7 over a period from 0900 to 1000 UT on July 11, 2000. The upper panel shows the echo power in dB, the middle panel shows the line-of-sight (LOS) Doppler velocity in m/s, and the bottom panel shows the Doppler spectral width in m/s.

negative values correspond to plasma movement away from the radar) and the bottom panel shows the Doppler spectral width in m/s. We utilized the Basyouhu scanning mode with 3 special camping beams (5, 7 and 9) as well as an optimized global scan. The beam sequence was as follows:

bs3-1) *0, 7, 4, 5, 8, 7, 12, 9, 2, 7, 6, 5, 10, 7, 14, 9, 1, 7, 13, 5, 3, 7, 11, 9,*
(G 0, 4, 8, 12, 2, 6, 10, 14, 9, 1, 13, 5, 3, 7, 11,)
(S 7, 5, 7, 9, 7, 5, 7, 9, 7, 5, 7, 9,)

(Beams on the 'G' line can be treated as part of the global scan, while beams on the 'S' line can be treated as special camping beams.)

The integration period was 3 s. Thus, data from beam 7 was obtained about every 12 s, while data from beams 5 and 9 were obtained about every 24 s. Data for an entire global scan was obtained about every 75 s. The global scan can be divided into 4 sub-scans to increase the time resolution.

The middle panel of Fig. 2 shows a pulsation-like oscillation with a period of about 5 to 10 mins. The oscillation persists throughout the shown period, and a very clear LOS Doppler velocity enhancement is present at around 0935 UT.

Figure 3 shows an LOS velocity map for the period just prior to the observation of

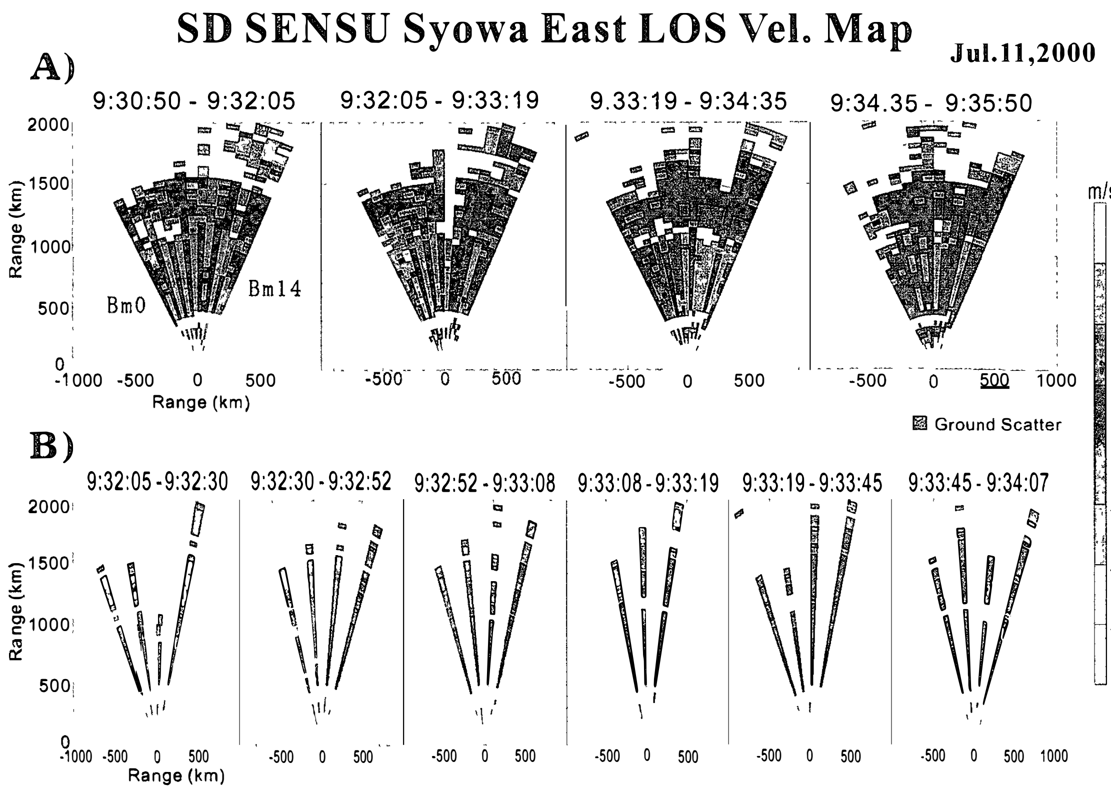

Fig. 3. Line-of-sight velocity map for the period around 0933:20 UT on July 11, 2000. A) The upper 4 plots show a series of consecutive velocity maps. Each map shows all of the global scan beams. B) LOS velocity map produced using consecutive sub-scans over a 2-min period between 0932:05 and 0934:07 UT. The map corresponds to the second and partly to the third maps in Fig. 3A.

the velocity enhancement. The upper panel (the 4 plots in the Fig. 3A) shows a series of consecutive velocity maps. Each map shows the results of all the global scan beams. The LOS velocity was almost negative (red color) throughout the radar field of view (FOV) for the first plot from 0930:50 to 0932:05 UT. About 1 min after the first plot period, the LOS velocity completely changed to positive (blue color) throughout the entire FOV (see third and fourth plots). This change occurred very rapidly, and the second plot period from 0932:05 to 0933:19 can be regarded as a very fast transient phase. It is very difficult to identify the temporal and spatial signatures of the transient process in detail using only this data. However, the global scan can be divided into 4 sub-scans, as described above. Figure 3B shows the LOS velocity map formed by consecutive sub-scans over a 2-min period from 0932:05 to 0934:07 UT that corresponds to the second and partly to the third maps in Fig. 3A. Using these sub-scan time-evolution maps, we can clearly determine that the positive (blue-colored) region passed over beam 14 through beam 0 within a period of one minute.

To characterize the rapid change in the LOS velocity map more clearly, Fig. 4 summarizes the velocity change at a range gate of 14 (about 810 km away from the Syowa radar) for all the observed beams during a period from 0932:00 to 0934:40 UT. The horizontal axis is the universal time (UT) and the vertical axis represents the beam

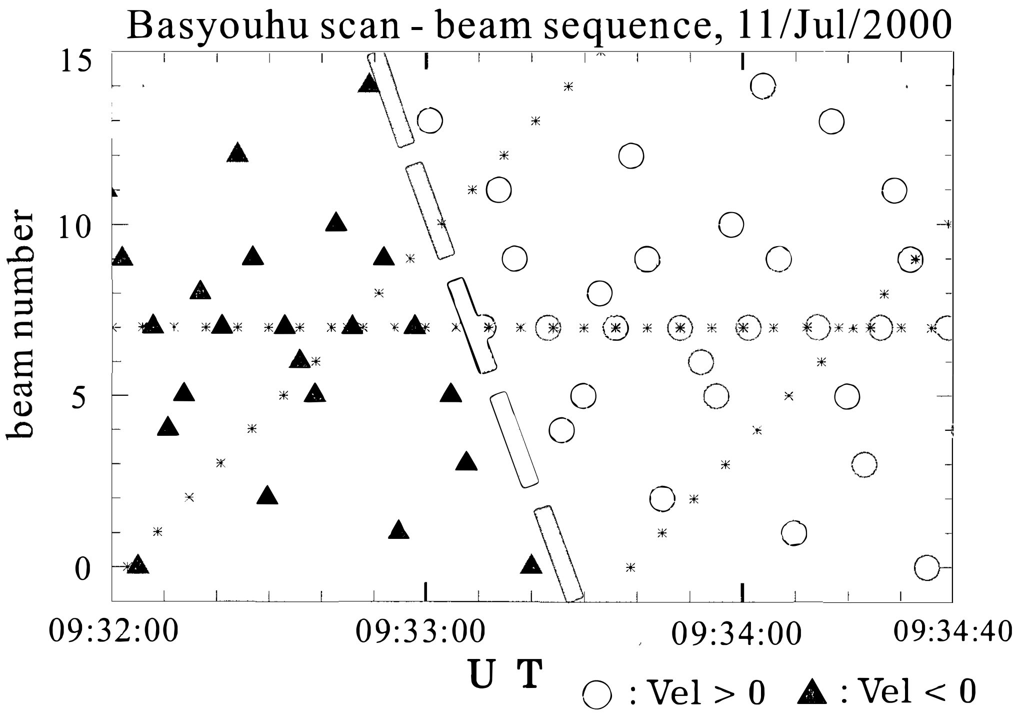

Fig. 4. Line-of-site velocity change at a range gate of 14 (about 810 km away from the Syowa radar) for all of the observed beams over a period between 0932:00 and 0934:40 UT on July 11, 2000. The horizontal axis is the universal time (UT) and the vertical axis represents the beam number. The triangles represent a negative LOS velocity observation (red-colored region in Fig. 3) and the circles represent a positive LOS velocity observation (blue-colored region). The asterisks show the beam sequence in case of normal global scan with a high time resolution camping beam (7) and an integration period of 3 s. The thick dashed line shows the sharp boundary between the negative velocity region and the positive velocity region.

number. Each triangle represents a negative LOS velocity observation (red-colored regions in Fig. 3) and each circle represents a positive LOS velocity observation (blue-colored regions in Fig. 3). A sharp boundary between the negative velocity region and the positive velocity region can be clearly seen and is shown as a thick dashed line on the figure. This figure only shows the results for range gate 14, but most of the range gates between ranges 7 and 20 show almost the same results as those predicted by the velocity maps in Fig. 3. This means that the transient front passed through the entire FOV westward, *i.e.* anti-sunward, for about 35 s. This result implies that the transient process passed at a speed of about 20 km/s through the region of the ionosphere observed by the radar. The scientific interpretation of this transient phenomenon is beyond the scope of this small paper and will be discussed in a separate report. The asterisks in Fig. 4 show the beam sequence for a normal global scan and a high time resolution camping beam (beam 7) with an integration period of 3 s. If this simple sounding mode had been used on the day that the transient phenomenon was observed, the temporal and spatial signature of this very rapid movement would never have been detected. Thus, the Basyouhu mode, whose beam sequence appears to be almost random, actually enables very rapid transient phenomena to be detected.

4. Summary and concluding remarks

We have developed several new sounding modes for SuperDARN HF radars. One of these, the Nasu mode, is a multi-purpose, universal radar control program that can be used to detect short-term transient phenomena, especially phenomena observed using special camping beams.

Another new sounding mode, the Basyouhu mode, enables both special camping beams and global scanning beams to be optimized, allowing higher time resolution special beam data and global convection patterns to be simultaneously obtained. Using this new mode, a very rapidly moving transient phenomena (about 20 km/s) passing through the radar FOV was detected without any ambiguity or uncertainty. This type of phenomena has never been detected by the SuperDARN radars. Thus the new sounding modes can be utilized as powerful tools to detect the rapid movements of transient phenomena in the ionosphere.

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