Velocity of small-scale auroral ionospheric current systems over Indian Antarctic station Maitri

Girija Rajaram, A N Hanchinal, R Kalra, K Unnikrishnan, K Jeeva,
M Sridharan and A Dhar

Indian Institute of Geomagnetism, Colaba, Mumbai 400 005, India

The Indian Antarctic station Maitri (geog. 70°45′S, 11°45′E, geom. 66°.03S, 53°.21E) occupies a sub-auroral location during magnetically quiet conditions ($\Sigma Kp < 10$), but attains an auroral position when the auroral oval shifts equatorwards with increasing strength of magnetic disturbance. At the latter times, triangulation with 3 fluxgate magnetometers located at the vertices of a suitable triangle provides a means of monitoring mobile auroral ionospheric current systems over Maitri. The spacing between the magnetometers is typically kept at 75–200 km, keeping in mind the scale-sizes of ~ 100 km for these mobile current systems. This work reports the results of two triangulation experiments carried out around Maitri in January 1992 and January 1995, both during Antarctic summer. The velocities estimated for pulsations of the Pc4 and Pc5 type were about 0.59 km/sec in the direction 102°.7 east of due north, in the first case, and about 1–3 km/sec in the second case in the east-west direction.

While several magnetometer arrays exist in the northern auroral regions (e.g., the Alberta array in Canada, the Alaskan array in the U.S. and the IMS Scandinavian array), there is no report in literature of triangulation through arrays in Antarctica, except for a one-day study by Neudegg *et al* 1995 for ULF pulsations of the Pc1 and Pc2 type. The velocities obtained for the Pi3 type of irregular pulsations over Antarctica in the present study tally well with those obtained for northern auroral locations.

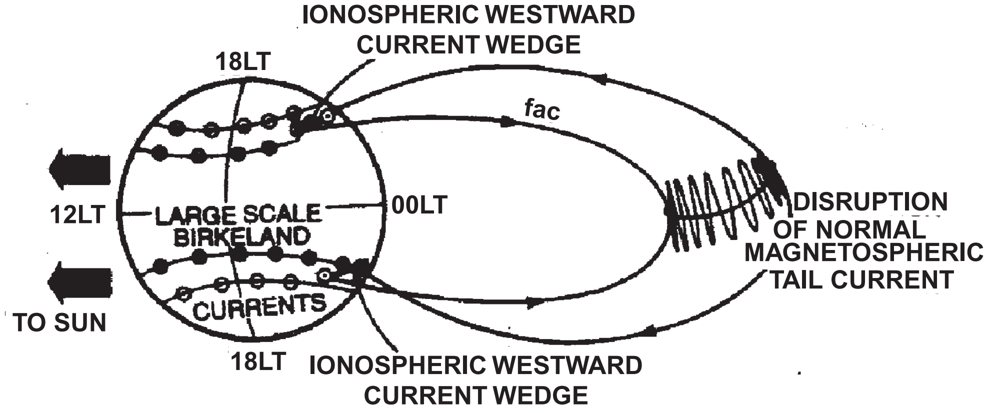
1. Introduction

The Indian Antarctic station Maitri (MAI) is located at geog. 70°45′S, 11°45′E (geom. 66°.03S, 53°21E), in the Schirmacher oasis region of Queen Maud land, and lies north of the Wohlthat mountain chain. The area around MAI is rocky, and it receives relatively little snow, which makes it ideal for operating round-the-year as an Antarctic research station. Studies of the variations in the X, Y, Z geomagnetic components continuously recorded at MAI indicate it to be a sub-auroral station during magnetically quiet (Q) times i.e., the geomagnetic signatures at MAI are those left by the southern limb of the quiet time S_q current loop in the southern hemisphere. With the onset of magnetic disturbance (D) and the equatorward shifting of the auroral oval, MAI gradually comes into the oval, and clearly records the geomagnetic signatures of the westward auroral electrojet (WAE) in the dawn sector, and of the eastward auroral electrojet (EAE) in the dusk sector (Hanchinal *et al* 1996). This inference is further supported by the visual and photographically recorded shifts in the ‘aurora australis’ from a position well southwards (polewards) of MAI during Q times to a position directly above MAI or even north (equatorwards) of the station during D times.

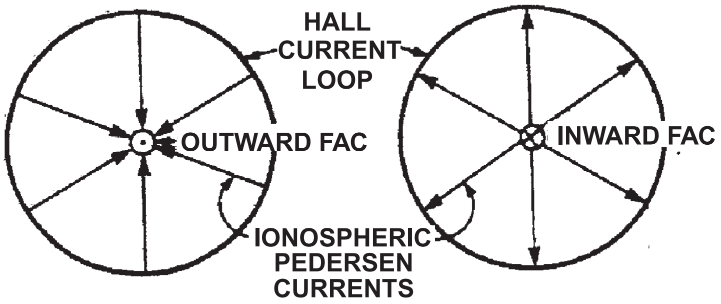
The physics behind the present magnetometer triangulation experiment at MAI is as follows. It is an established fact that the auroral regions of the Earth form the locale for field-aligned currents arising from precipitation of energetic magnetospheric

Keywords. Geomagnetic pulsations; mobile auroral current systems; field-aligned currents; Antarctica.

Proc. Indian Acad. Sci. (Earth Planet. Sci.), **111**, No. 1, March 2002, pp. 51–62



a) MAGNETOSPHERE-IONOSPHERE COUPLING THROUGH SMALL-SCALE CURRENT WEDGE



b) SMALL-SCALE LOOPS OF HALL CURRENT IN AURORAL IONOSPHERE CLOCKWISE OR ANTICLOCKWISE DEPENDING ON HEMISPHERE AND DIRECTION OF FAC

Figure 1. Disruption of the normal magnetospheric tail current during geomagnetic disturbance, causes Field-Aligned Currents (FAC) to flow into a wedge shaped region of the auroral ionosphere. The inward and outward FAC at the edges of this wedge give rise to ionospheric Pedersen currents as shown. The interaction between the Pedersen electric field and the geomagnetic field generates near-circular Hall current loops in the auroral ionosphere. These small scale current loops drift under the $E \times B$ effect westwards in the dusk sector and eastwards in the dawn sector, and it is their magnetic signatures which are detected by fluxgate magnetometers on the ground.

electrons into the ionosphere. The field-aligned currents can be of large-scale sheet type (Boström 1975) or of a localised current wedge type (McPherron *et al* 1973). The former are almost always present in the auroral regions in concert with diffuse aurora, while the latter manifest during magnetically disturbed conditions such as storms and substorms. The IMS Scandinavian magnetometer/riometer chain succeeded in establishing that Field-Aligned Currents (FAC) form the boundaries of this wedge. On the western edge strong outward directed FAC corresponding to hot magnetospheric electrons precipitating into the ionosphere, and on the eastern edge weaker inward directed FAC corresponding to cold ionospheric electrons flowing upwards were established (Opgenoorth *et al* 1980; Opgenoorth and Baumjohann 1984). Figure 1(a) shows the mapping of these FAC from the equatorial plane of the magnetosphere following the disruption of the normal cross-tail current. The FAC maps into the auroral ionosphere as a westward current wedge. Corresponding to the inward and outward-directed FACs, are small-scale loops of Hall current which are formed in the auroral ionosphere.

Fukushima (1974, 1975, 1976) in a series of papers showed that when field-aligned currents flow from the magnetosphere to the ionosphere they generate radial Pedersen electric fields in a uniformly conducting ionosphere, radially inward for an outward FAC and radially outward for an inward FAC as shown in figure 1(b). It is easily seen that at every point in the vicinity of the FAC, the radial Pedersen electric field interacts with the practically vertical geomagnetic field (at auroral latitudes) to give rise to an $E \times B$ Hall current vector which continuously changes direction to form a loop. This is how small-scale Hall current loops are formed in the auroral ionosphere, and their circular pattern would be distorted in a non-uniformly conducting ionosphere. These current loops in the ionosphere drift eastwards in the dawn sector and westwards in the dusk sector, reflecting the $E \times B$ drift which originates in large-scale magnetospheric convection occurring in the equatorial plane. It is the signatures of these drifting ionospheric current loops which are recorded by ground-based magnetometer triangulation experiments at auroral latitudes, as time-lags in geomagnetic pulsations.

Pulsations on auroral magnetograms of the Pi3 category (long-period pulsations Ps6 and WTS with time-periods exceeding 150 sec), are often associated with changes in the form and structure of visible aurora i.e., Omega bands in the dawnside and the Westward Travelling Surges in the duskside. Both these features are believed to be associated with the localised small-scale current systems described above, which drift under the influence of the magnetospheric convection electric field, in the magnetic east-west direction in the auroral ionosphere (Opgenoorth *et al* 1983). Such drifting currents form preferentially during periods of isolated substorms or a series of substorms comprising a storm (Buchert *et al* 1990).

The speed and direction of drift of these mobile current systems can be estimated from time-lags in their geomagnetic signatures on ground-based magnetometers (in the X, Y, Z components) as they drift in the auroral ionosphere from one location to another. An array of several magnetometers deployed in the magnetic north-south and east-west directions forms a very suitable method for obtaining the velocity of these drifting auroral current systems. Magnetometer arrays (all in the northern hemisphere) have been used very effectively for this purpose e.g., the Alberta array in Canada (Kisabeth and Rostoker 1973), the meridian chain in Alaska (Akasofu *et al* 1971), and the Scandinavian array (Opgenoorth and Baumjohann 1984). Operating such arrays of magnetometers in the difficult terrain and the harsh climatic conditions of Antarctica is a formidable task even in summer, and the most we have been able to achieve is triangulation. This is done by deploying 3 magnetometers at the vertices of a triangular area around MAI; the sides of the triangle are about 76–200 km, in view of the scale-sizes of these small-scale drifting auroral current systems (Gorney 1991).

In the present work, the results obtained during two such Antarctic summer campaigns are discussed, the first during 6th–8th January 1992, and the second during 30th January – 1st February 1995. These fluxgate magnetometer triangulation experiments were conducted by the Indian Institute of Geomagnetism (Mumbai) as part of the 11th and the 14th Indian Scientific Expeditions to Antarctica.

2. The experimental set-up

The three fluxgate magnetometers in both campaigns were oriented so as to respond to variations in the Y (east-west), X (north-south) and Z (vertical) components of the Earth's magnetic field. The voltage variations of the magnetometers were recorded in two modes. In the first mode the daily variation (DV) was recorded on analog chart-recorders with a chart-speed of 3 cm/hr, and depending on the magnetic disturbance level, the sensitivity of the chart-recorder was varied between 10 V Full Scale Deflection (FSD) to 40 V FSD. In the other mode only pulsations with time-periods 30 sec to 3000 sec (i.e., frequencies 33 mHz to 0.33 mHz covering the entire Pc3 to Pc6 range) were retained with the help of electronic filters, and were recorded at a speed of 12 cm/hr. The voltage variations were also recorded in digital form on solid state data-loggers, but for these two initial campaigns, digital data could not be obtained simultaneously at all 3 stations, and hence only analog data have been utilised for this study. Simultaneity of recordings at three locations was ensured by synchronising crystal-controlled clocks at the start of the experiment, and checking them at the end of the experiment. A block diagram of the experimental set-up is shown in figure 2.

3. Observations

3.1 *The triangulation experiment of January 1992*

Over the period 6th – 9th January 1992 (Antarctic summer) three fluxgate magnetometers were operated at the vertices of a triangular area located in the vicinity of MAI with sides measuring roughly 75, 157 and 217 km. The three vertices lie at Maitri (MAI), Dakshin Gangotri (DG), and Payer's Camp (PAY), and their geographic and geomagnetic coordinates are given in table 1. A geological map of the area in which these are located is shown in figure 3 (courtesy, Geological Survey of India, Faridabad). The three locations were expected to take observations for at least a week during January 1992, but blizzard conditions brought down the operating time to only 3 days, namely 6th – 8th January 1992. This interval was a rather disturbed one with

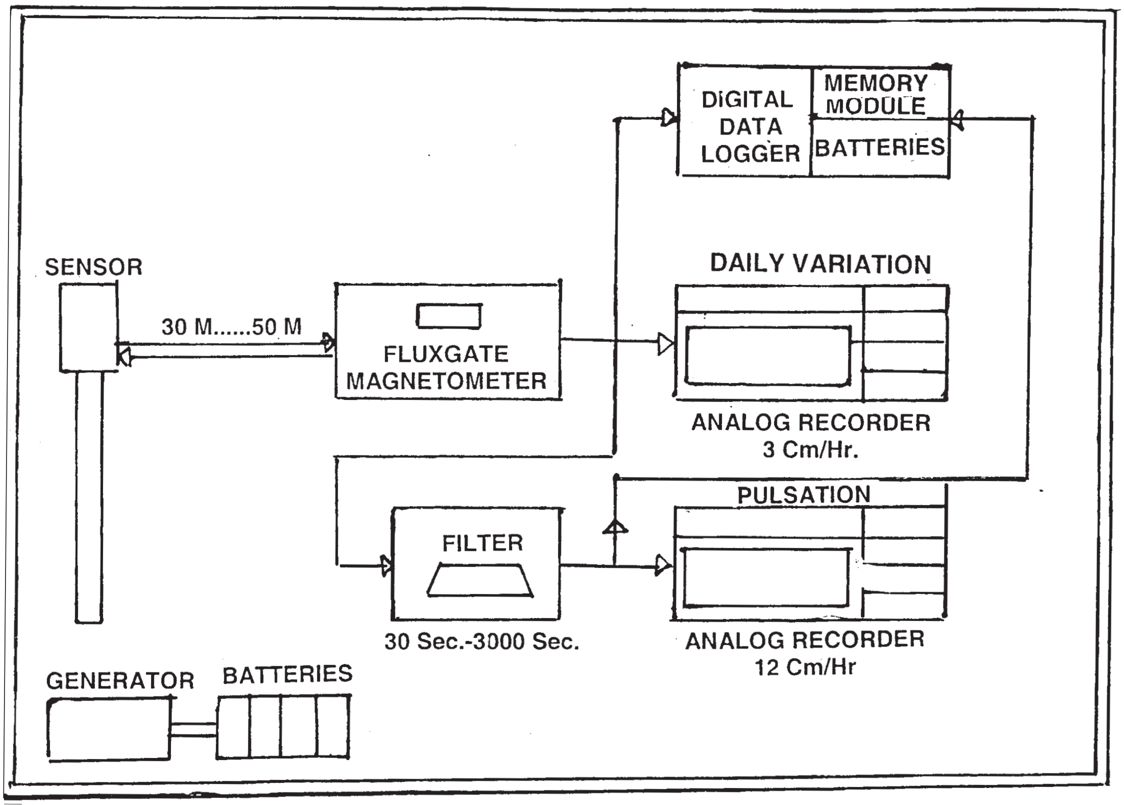


Figure 2. Block diagram of fluxgate magnetometer set-up used to record daily variations and pulsations in the X, Y and Z components of the geomagnetic field at Maitri, DG, Orvin Camp and Payer Camp.

ΣKp values of 22o, 17o and 25o on these three days respectively. A magnetic storm occurred on 8th January 1992 with SSC (storm sudden commencement) at 02:45 UT, and an amplitude of 190 nT in the X component. There was considerable pulsation activity of the Pi3 type with periods exceeding 150 sec (IAGA Bulletin No. 35, 1975, p 145) prior to the storm, namely around 22 UT on 7th January. The K_p values for the 3 hourly intervals 18–21 UT, 21–24 UT, and 00–03 UT were 3-, 2o and 3- respectively. Clear time-lags were noted in the occurrence of similar geomagnetic variations at the three locations.

Figure 4 shows the magnetic variations recorded in the X, Y, Z components at the locations MAI, PAY and DG in the night hours of 7th January 1992; on the lowest set of curves are marked the time-intervals 21, 22, 23 and 00UT valid for the X component of all the 3 stations. The traces represent the electronically filtered voltage output for variations with time-periods lying between 30 sec and 3000 sec. Eight clear sets of pulsations in the X, Y and Z components which showed time-delays between pairs of stations have been selected using the feature that the chart-speed was 12 cm/hr. Time-lags for 8 events between MAI-PAY are listed in table 2 and the times of the events are given in UT. The average time-lag works out to be 3.6 min. Determination of time-lags between DG-PAY was complicated by the feature that the pulsations were very diluted at DG. Only 2 clear pulsations could be identified for the DG-PAY magnetograms, and these are also listed in table 2. The average time-lag for these two events is 3.5 min. The reason for the suppressed variations at DG is discussed later.

Figure 5 is drawn to the scale 1° latitude = 0.4° longitude, which is appropriate for the location of MAI. This is because while 1° latitude $\sim$ 110 km

Table 1.

	Geographic		Geomagnetic	
Location	Latitude	Longitude	Latitude	Longitude
Dakshin Gangotri	70°05′S	12°00′E	65°.48 S	54°.18 E
Maitri	70°45′S	11°45′E	66°.03 S	53°.21 E
Payer Camp	71°51′S	14°29′E	67°.41 S	53°.70 E
Orvin Camp	71°40′S	09°35′E	66°.48 S	50°.58 E

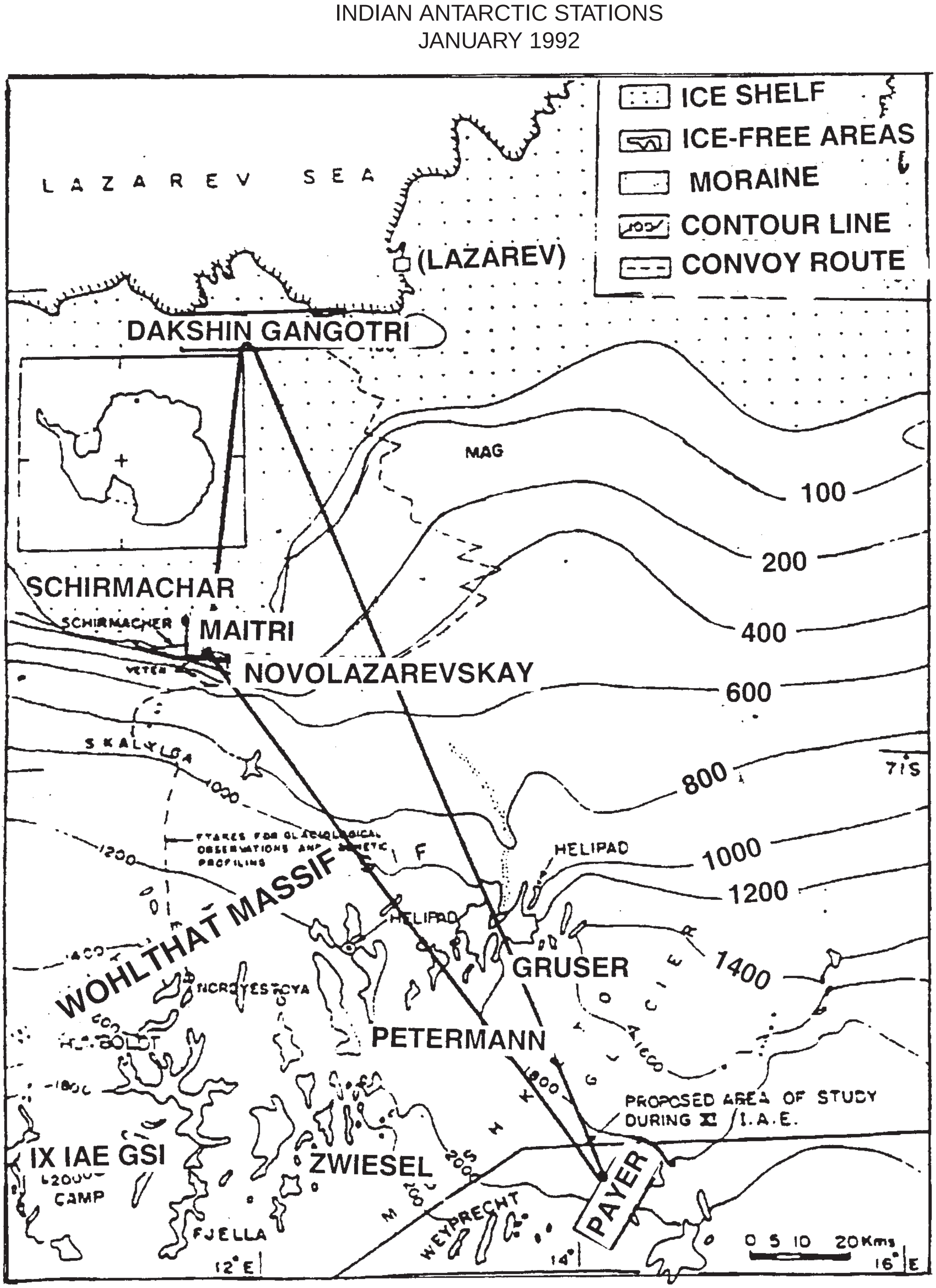


Figure 3. Geological elevation map of area in which fluxgate magnetometers were operated simultaneously at the three locations Dakshin Gangotri (DG), Maitri (MAI) and Payer Camp (PAY) during January 1992. DG is located on the ice-shelf, MAI in the Schirmacher oasis region and PAY in the Wohlthat Mountains region. The distance between the three stations varied between 75 and 218 km. (Courtesy Geological Survey of India, Faridabad).

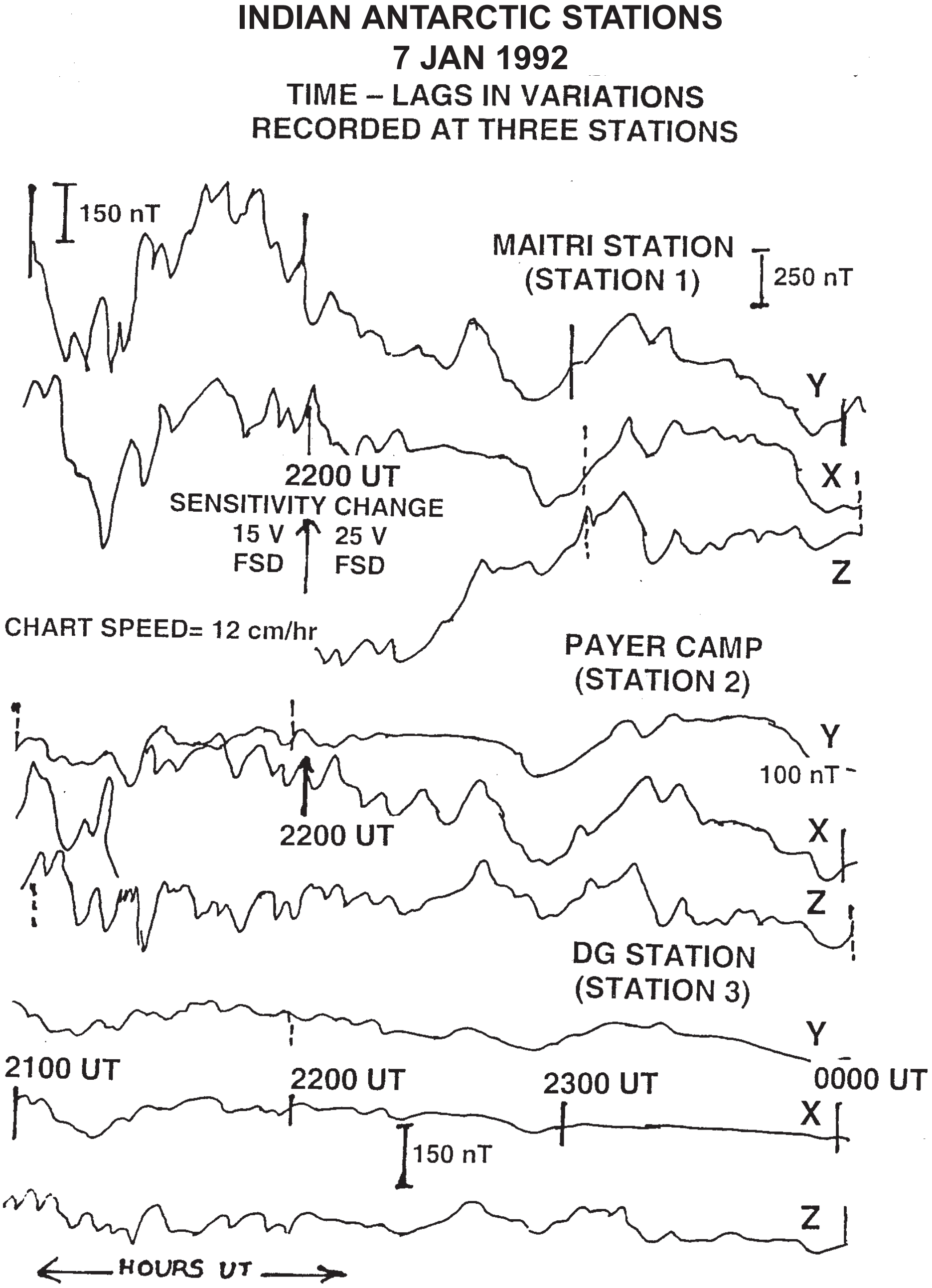


Figure 4. Simultaneous geomagnetic pulsations at DG, MAI and PAY between 21:00 UT on 7th January 1992 and 00:00 UT on 8th January 1992. The time lags between similar pulsations has been used to estimate the velocity of causative ionospheric current systems which drifted over the three stations. The three geomagnetic components X, Y and Z have inadvertently been recorded in different order at the different locations and hence are marked against the respective curves.

for all latitudes, the distance between 1° longitude diminishes with increasing latitude, and is about 42 km at 62° geog. latitude. The values of the angles of triangle ABC formed by the three locations is shown in figure 5. The arrow marked N is the line of geographic north-south, and the dashed line $A'C'$ indicates a possible path of propagation of the wave-front of the mobile, small-scale auroral current systems, over the station MAI. AA' and CC' are perpendiculars dropped on this path from A (DG station) and C (PAY station). This path of propagation $A'C'$ is assumed to make an angle θ with the north-south line. The unknowns therefore are this angle θ, and the velocity V with which the wave-front propagates; these are obtained through trigonometrical means from figure 5. To assist in this calculation, two further angles are used, namely:

the angle made by the side AB with the north-south line – β

the angle made by the side BC with the north-south line – α.

Both these are measured and are known. The two equations used to evaluate V and θ are:

$$V = \frac{A'C'}{\mathcal{T}_{AC}} \tag{1}$$

where $\mathcal{T}_{AC}$ is the time-lag observed between similar pulsations at DG and PAY.

Similarly,

$$V = \frac{BC'}{\mathcal{T}_{BC}} \tag{2}$$

where $\mathcal{T}_{BC}$ is the time-lag observed between similar pulsations at MAI and PAY.

These equations can be solved through trigonometric methods (Singh *et al* 1977), using the angles shown in figure 5. To illustrate this the average values of (3.5×60) sec for $\mathcal{T}_{AC}$ and (3.6×60) sec for $\mathcal{T}_{BC}$ are used. The velocity V of the causative small-scale auroral ionospheric current system for this event works out to be 0.59 km/sec, and the angle θ which the velocity vector V makes with the north direction is $102°.7$.

In this work we have used average time lags to estimate the velocity of the mobile auroral current systems, because the accuracy of reading time-lags from the charts is limited. Time-lags obtained from digital data after using appropriate mathematical filtering techniques would be far more accurate, but unfortunately the digital data recorded was corrupted in the intense cold at the Camp station.

3.2 *The triangulation experiment of January 1995*

During the summer campaign of the 14th Indian Antarctic Scientific Expedition, two fluxgate magnetometers were operated at the same locations as earlier, namely at MAI and DG. The third location was however at a different position, namely at Orvin Camp located in the Conrad mountains of Antarctica. The geographic and geomagnetic coordinates of Orvin are shown in table 1. The sides of the triangle formed in this case were 75, 190 and 228 km, as shown in figure 6. The three stations in this case were operational from 22nd January 1995, but adverse weather conditions forced the operation of Orvin as an unmanned station. This resulted in only a few hours from three days (30th January – 1st February 1995) of simultaneous data on the X, Y, Z components.

Table 2. *Time-delays for pulsation events between Maitri and Payer – 7th January 1992.*

Event no.	Time of event (UT)	Delay (cm)	Delay (min)
1	21:02	0.7	3.5
2	21:15	1.0	5.0
3	21:58	0.7	3.5
4	22:00	1.0	5.0
5	22:07	0.5	2.5
6	22:10	0.7	3.5
7	23:05	0.6	3.0
8	23:10	0.5	2.5

Average time-delay = 3.6 min.

Time-delays for pulsation between DG and Payer.

1	21:02	0.6	3.0
2	21:15	0.8	4.0

Average time-delay = 3.5 min.

Figure 7 shows stacked magnetograms (Daily Variation Charts run at 3 cm/hr) for MAI, ORV and DG from 30th January 1995, 17:00 UT to 31st January 1995 10:00 UT; some data for DG after 03:00 UT is missing. The magnetograms have been arranged in a manner such that the major event, a substorm between 23:30 UT and 03:00 UT, characterised by positive Y and negative X and Z lies in a stacked manner at the three locations. Time in UT and Recorder Sensitivity in Volts FSD are indicated on the figure.

Table 3 shows the time differences and time-lags between similar pulsations at MAI and ORV for events 1 to 9 occurring between 21:00 UT of 30th January 1995 and 07 UT of 31st January 1995. Time-lags vary between 1 minute to 4 minutes, corresponding to the causative current systems having speeds of 3.2 km/sec to 0.79 km/sec respectively. The average time-lag works out to be 2.44 minutes giving an average speed of 1.16 km/sec. The timings of the pulsations would suggest that for events 1 to 6, the causative current system moved eastwards, i.e., from Orvin to MAI. Events 7, 8, 9 seem to have occurred earlier at MAI and later at Orvin i.e., the localised current systems move westwards. If one separates out the pulsations on this basis, the average time-lag for events 1 to 6 (21:00 UT – 03:00 UT) is 2.67 minutes and the average velocity of the causative current system is 1.02 km/sec in the eastward direction. Similarly the average time-lag for the events 7, 8, 9 from 0500 to 0640 UT is 2 minutes, and the velocity works out to 1.58 km/sec in the westward direction.

4. Conclusions

In the case of the January 1992 event, the current system responsible for the time-lags in the pulsations shown in figure 4 drifted over the Indian Antarctic station MAI with an average speed of 0.59 km/sec, at an angle of $102°.7$ east of north. In the case of the January 1995 event depicted in figure 7, the average velocities were 1.02 km/sec in the

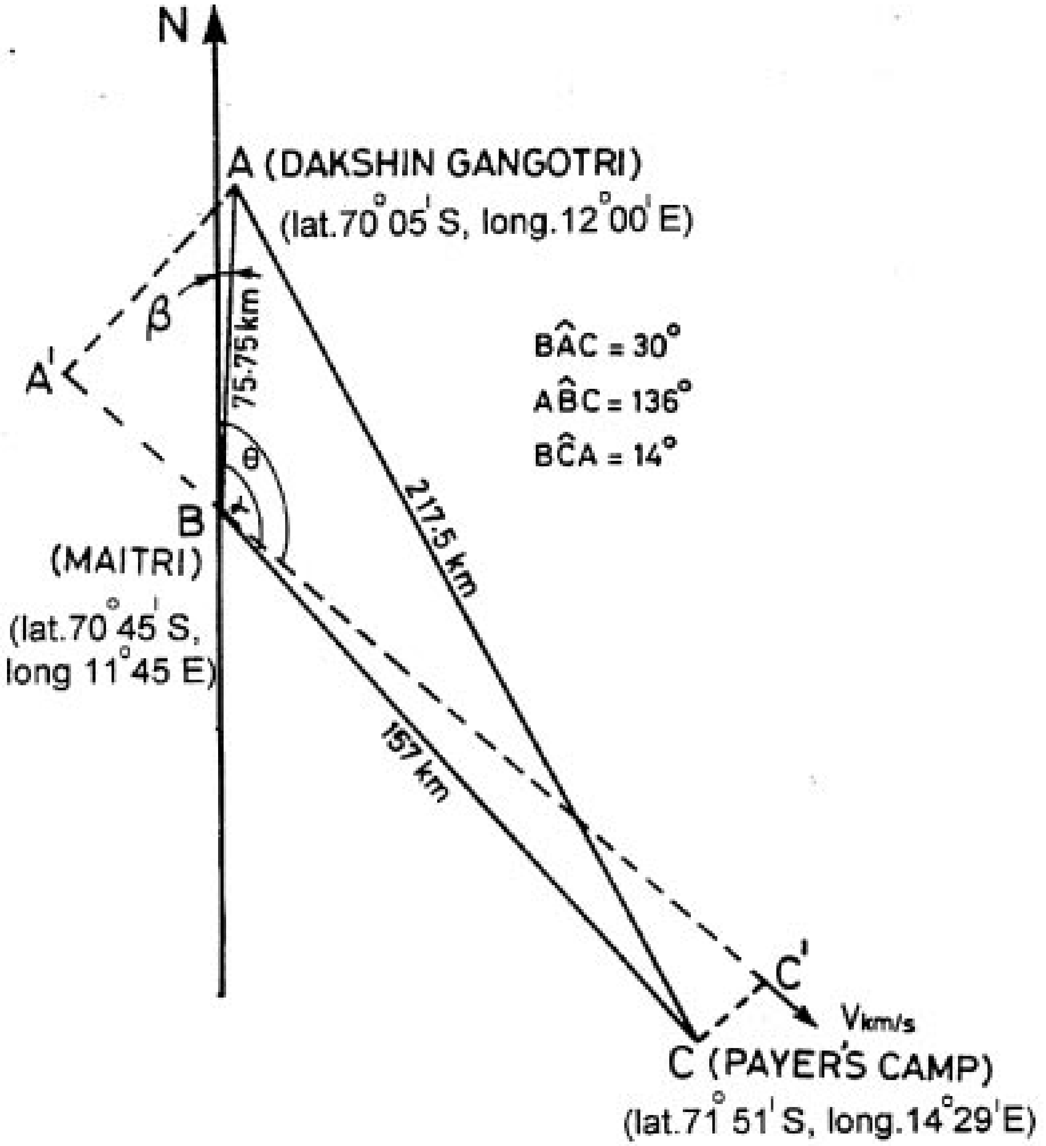


Figure 5. Figure drawn to scale shows the various angles and the distances between the Indian Antarctic locations involved in the trigonometrical estimation of the velocity. The line $A'C'$ shows the possible path of the overhead ionospheric current system and it makes an unknown angle θ with the NS line. AA' and CC' are perpendiculars dropped from A (DG) and C (PAY) on to the line $A'C'$, which it may be noted, passes through B (i.e., the station Maitri).

eastward direction, and 1.58 km/sec in the westward direction. The pulsations in both these cases occurred during magnetically disturbed conditions, but they are not clear regular pulsations of the Ps6 type (Saito and Morioka 1972) or of the Pip type (Raspopov *et al* 1971). They are more like irregular pulsations of the Pi3 type, with periods exceeding 150 sec (IAGA Bulletin No. 35, 1975, p. 145).

We would thus conclude that the velocities of the localised auroral current systems responsible for the pulsations seen at the Indian Antarctic stations for these events (January 1992 and January 1995) tally with values observed by other workers at auroral locations [cf. 0.66 km/sec obtained by André and Baumjohann (1982); 1.9 km/sec to 2.3 km/sec by Tighe and Rostoker (1981); 0.8 km/sec by Kawasaki and Rostoker (1979); 0.6 km/sec to 1.6 km/sec by Rajaram *et al* (1986)]. It may be mentioned that all these observations are for the Arctic auroral zone. The authors are not aware of any small-scale magnetometer array studies in the Antarctic region, except for the one-time study by Neudegg *et al* (1995) of the velocity pattern of Pc1-Pc2 ULF pulsations. The only other study is that of Dunlop (1994), which is essentially a study of the magnetospheric origin of simultaneous pulsations at the distantly-spaced (exceeding 200 km) network of Australian stations, and is not a velocity determination.

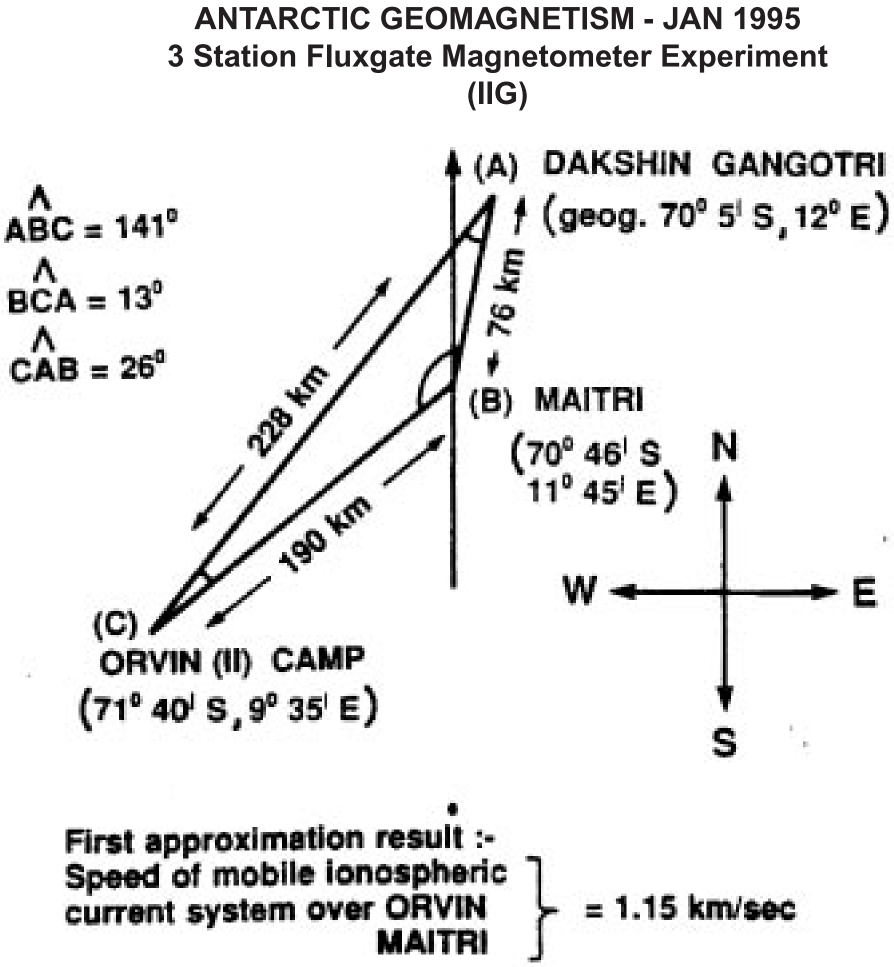


Figure 6. Figure showing the locations operated during January 1995 with their geographical latitude and longitude. Orvin Camp was located in the Conrad Mountains of Antarctica. The sides of the triangular set-up were roughly 75, 190 and 228 km.

5. Discussion

The auroral regions of Earth play a special role in transfer of energy between the distant geomagnetosphere and the Earth's near-space environment i.e., the ionosphere. The geomagnetic field lines preferentially channelise plasma emissions from the Sun towards high northern and southern latitudes of Earth leading to strong, inhomogeneous localised current systems in the auroral ionosphere and hence to severe magnetic fluctuations on ground-based magnetograms, notably at auroral latitudes. Monitoring of pulsations in the magnetic field variations at auroral locations separated by about 100–200 km (the scale-size of these current systems) can provide clues to the understanding of magnetosphere-ionosphere electrical coupling.

The two events discussed in this paper use analog chart-records for the determination of time-lags in pulsations observed at the vertices of the relevant triangle, and have their own limitations:-

- It is impossible to stack Y, X, Z traces obtained on Riken-Denshi recorders exactly beneath one another such that the time-axis is the same for all three curves. This is because the recorders themselves are designed in such a manner, that each of the three pens for recording Y, X and Z at any point in time, is a little ahead of the other so that the pens do not run into one another during rapid, large fluctuations which occur at high latitude locations.

  The traces could be redrawn so as to render their time-axis uniform but then they would undergo some artificial changes. We have preferred to avoid this and have used xeroxes of the original charts (cf figure 4 and figure 7).
- The cold temperatures of $-30°$ C and below, obtained at the Payer and Orvin Mountain camp stations in the two campaigns of 1992 and 1995 did affect the speed of the analog recorders operating at those locations. Times were matched here from the expected chart speed for the major time-interval under study i.e., 22 UT-23 UT for 7th January 1992, and 00-03 UT for 30th – 31st January 1995. Normally, automatic electronically-controlled time marks

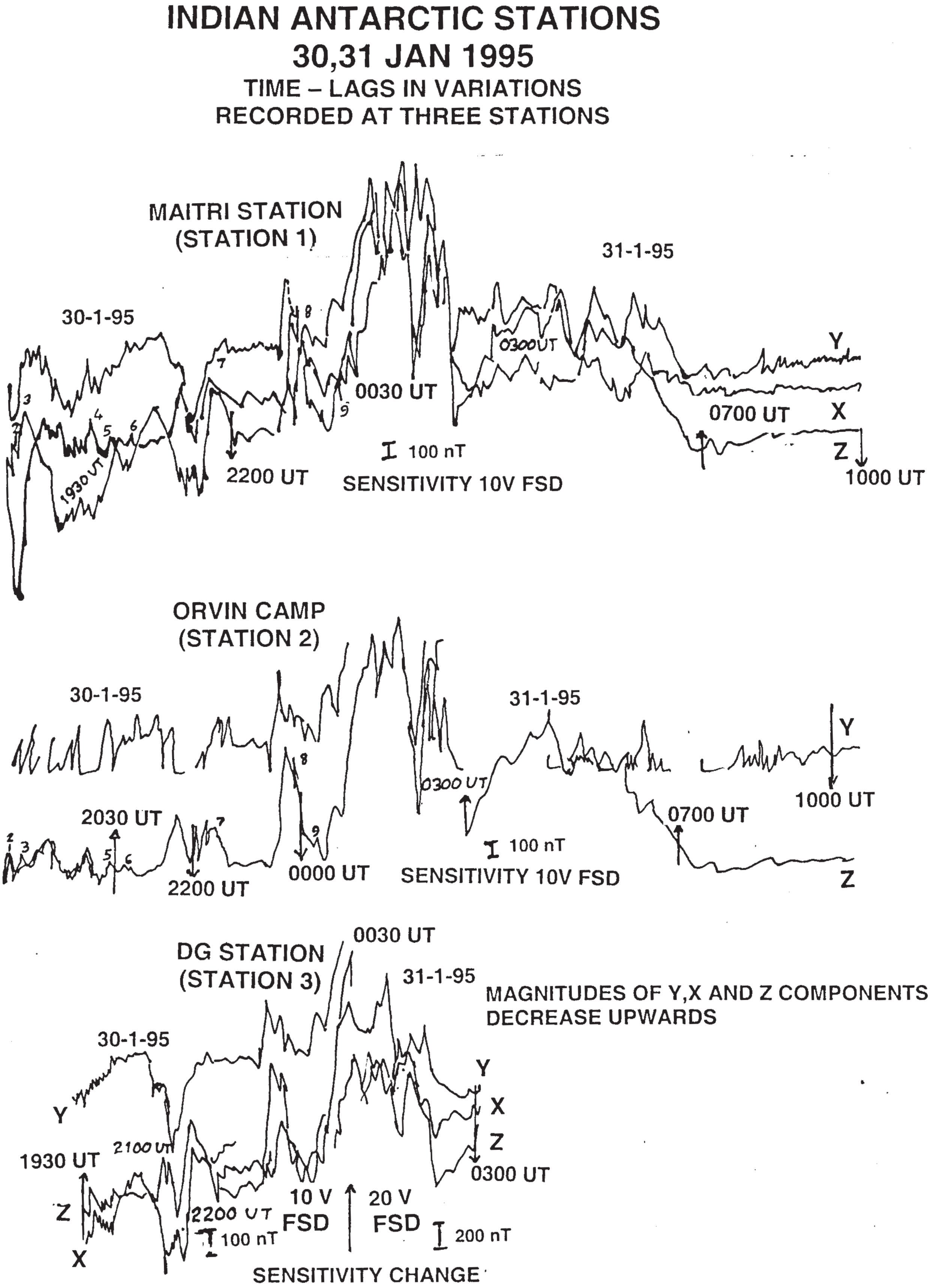


Figure 7. Simultaneous geomagnetic Daily Variations (DV) run at 3 cm/hr. For DG, Maitri and Orvin during 30th January 1995 17:00 UT and 31st January 1995 10:00 UT; some amount of data for DG is missing.

Table 3. *Time-delays for pulsation events between Maitri and Payer – 30th January 1995.*

Event No.	Time of event (UT)	Delay (cm)	Delay (min)
1	21:40	0.5	1.0
2	22:20	1.0	2.0
3	01:20	1.0	2.0
4	01:40	2.0	4.0
5	02:20	1.0	3.0
6	03:00	2.0	4.0
7	05:00	−1.5	−3.0
8	06:15	−0.5	−1.0
9	06:40	−1.0	−2.0

Average time-delay = 2.44 min.

are generated every hour, but even these stalled at times in the severe cold.

It is for these reasons that while individual velocities for individual events has been estimated, no attempt has been made to project these velocities as a function of time. It is very likely that the velocities would indeed be a function of LT and it would be certainly worthwhile to estimate the LT variation of velocities of the mobile small-scale auroral current loops as these are known to differ between the dawn and dusk sectors (Wiens and Rostoker 1975). This however requires very accurate data in digital mode, which could not be obtained during these campaigns of January 1992 and January 1995, because the digital data-loggers malfunctioned in extreme negative temperatures which prevailed at the Payer and Orvin camp stations.

With digital data, it is perfectly feasible to generate stacked magnetograms of the Y, X, Z traces such that the time axis is the same for all three curves. Under these conditions it is feasible too to draw neat lines joining identical pulsation events at the different stations, so that the reader can visually estimate the time-lags. Fortunately, based on the experience of the 1992 and 1995 campaigns, good digital data could be obtained at all three locations in the Indian Antarctic magnetometer triangulation campaigns of January 1996 and January 2001. These digital results will be presented in a separate paper, and will hopefully present far more lucid visual pictures than could be presented in the present work based on analog records.

Finally a few lines about the variations at DG being very small compared to those at MAI and PAY. This could be (1) genuine due to the small-scale current system moving directly over MAI and Payer, and giving DG a wide berth. This would indeed be the case for the current system obtained moving at an angle 102.7°E of north at MAI. (2) The sensitivity of the Fluxgate Magnetometer at DG could also matter. Prior to this very first triangulation experiment we had not realised the importance of calibrating the instruments at our Standard Observatory in India. This is being regularly done ever since.

Acknowledgements

The authors are grateful to the Indian Institute of Geomagnetism for supporting the project of Antarctic Geomagnetism, and to the Department of Ocean Development, Government of India, New Delhi, for all travel and logistic support from India to Antarctica, in Antarctica, and back.

For the first Antarctic summer triangulation campaign of January 1992, the authors express their deep gratitude to the members of the Antarctic Division of the Geological Survey of India, Faridabad, for their support in establishing and maintaining the Payer Camp station in the Wohlthat mountains. They also supplied values of the angles and the distances used in the trigonometrical estimation of velocities of the small-scale current systems. The authors express their sincere appreciation to the helicopter pilots of the Indian Navy who carried out flights between Maitri, Dakshin Gangotri and Payer under very adverse conditions.

For the second triangulation campaign of January 1995, the authors thank the expedition leader, Dr. S D Sharma for full support, and Commander G S Sekhon and his flying crew of the Indian Navy, for providing the vital support and for the helicopter sorties needed during very inclement Antarctic weather. Our thanks go to Dr. Ranjan Kumar Gupta (BHU), Dr. B R Bejarniya, Mr. V Ravikant and Mr. A Kundu (GSI Team), Mr. S Satyakumar (WII) and Mr. Dinesh Mohan (DEAL) for their willing help throughout the expedition.

The authors are grateful to the two referees for their comments, which have helped in making this paper more lucid.

References

Akasofu S-I, Wilson C R, Synder A L and Perrault P D 1971 Results from a meridian chain of observations in the Alaska sector, 1; *Planet Space Sci.*, **19** 497

Ándre D and Baumjohann W 1982 Joint 2-D observations of ground magnetic and ionospheric electric fields associated with auroral current systems associated with eastward drifting omega bands; *J. Geophys.* **50** 194–201

Boström R 1975 Mechanisms for driving Birkeland currents, Physics of the hot plasma in the magnetosphere (ed) B Hultguist and L Stenflo. (N.Y.: Plenum Press) 431–447

Buchert S, Haerendeal G and Baumjohann W 1990 A model for the electric fields and currents during a strong Ps6 pulsation event; *J. Geophys. Res.* **95** 3733–3743

Dunlop I S, Menk F W, Hansen H J, Fraser B J and Morris R J 1994 A multistation study of long-period geomagnetic pulsations at cusp and boundary layer latitudes; *J. Atmos. Terres. Phys.* **56** 667–679

Fukushima N 1974 Equivalent current pattern for a field-aligned current into the auroral belt of enhanced electric conductivity Part I, Case of no charge – accumulation at the auroral zone boundaries; *Rep. Ionos. Space Res. Japan* **28** 207–218

Fukushima N 1975 Equivalent current pattern for a field-aligned current into the auroral belt of enhanced electric conductivity, Part II, Case of charge accumulation at the auroral zone boundaries; *Rep. Ionos. Space Res. Japan* **29** 31–38

Fukushima N 1976 Generalised theorem for no ground magnetic effect of conductivity currents connected with Pedersen currents in the uniform-conductivity ionosphere; *Rep. Ionos. Space Res. Japan* **30** 35–40

Hanchinal A N, Jeeva K, Dhar A and Rajaram G 1996 Response of geomagnetic field at Indian Antarctic station Maitri to increasing electromagnetic disturbance in Geospace; 12th *Indian Expedition to Antarctica Scientific Report* DOD Technical Publication No. **10** 47–57

Gorney D J 1991, Overview of auroral spatial scales; Auroral Physics (ed) C-I Meng, M J Rycroft and L A Frank, (Cambridge University Press) 325–334

Kawasaki K and Rostoker G 1979 Perturbation magnetic fields and current systems associated with eastward drifting auroral structures; *J. Geophys. Res.* **84** 1464–1480

Kisabeth J L and Rostoker G 1973 Current flow in auroral loops and surges inferred from ground-based magnetic observations; *J. Geophys. Res.* **78** 5573–5584

McPherron R L, Russell C T and Aubry M P 1973 Satellite study of magnetospheric substorms on 15 Aug 1968 : Phenomenological model for substorm; *J. Geophys. Res.* **78** 3131–3149

Neudegg D A, Borms G B, Traser B J, Menk F W, Morris R J, Hansen H J, Underwood M J 1995 Determination of Pc1-2 ULF wave velocity and direction using a closely spaced Antarctic magnetometer array; *Australian National Antarctic Research Expedition Report* 126–151

Opgenoorth H J, Pellinen R J, Mavrer H, Kuppers F, Heikkila W J, Kaila K U and Tanskane P 1980 Ground based observations of an onset of localised field-aligned currents during auroral break-up around magnetic midnight; *J. Geophys.* **48** 101–115

Opgenoorth H J, Oksman J, Kaila K U, Nielsen E and Baumjohann W 1983 Characteristics of eastward drifting omega bands in the morning sector of the auroral oval *J. Geophys. Res.* **88** 9171–9185

Opgenoorth H J and Baumjohann W 1984 Three dimensional current systems and electric fields during active aurora; *Proc. Conf. Achievements of the IMS,* 26–28 June 1984 Graz, Austria, ESA SP-217 (Sept 1984).

Rajaram G, Rostoker G and Samson J C 1986 Wave characteristics of Ps6 magnetic variations and their implications for convection flow in the magnetotail; *Planet. Space Sci.* **34** 319–329

Raspopov O M, Chernous A and Kiselev B V 1971 High latitude geomagnetic field pulsations and their use in the identification of magnetospheric parameters; *Geomagn. Aeron (Eng)* **11** 567–570

Saito T and Morioka A 1972 Dynamical characteristics of pulsating substorm Ps6; *Proc. Symp. On Magnetospheric substorm*, April 21–22, 1972 (Univ. of Tokyo: ISAS)

Singh Lakha, Vijaykumar P N, Garg S C, Tyagi T R, Bharadwaj R S, Dabas O P, Nagpal O P and Sengupta A 1977 Study of large and medium scale irregularities using 140 MHz ATS-6 Faraday rotation records from three stations; *Indian Jr. Radio and Space Phys.* **6** 245–249

Tighe W G and Rostoker G 1981 Characteristics of westward travelling surge during magnetospheric substorms; *J. Geophys.* **50** 51–67

Wiens R G and Rostoker G 1975 Characteristics of the development of the westward electrojet during the expensive phase of magnetospheric substorms; *J. Geophys. Res.* **80** 2109–2128

MS received 30 July 1999; revised 21 July 2001