Space Technology 5 multi-point measurements of near-Earth magnetic fields: Initial results

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Abstract. The Space Technology 5 (ST-5) mission successfully placed three micro-satellites in a 300 x 4500 km dawn-dusk orbit on 22 March 2006. Each spacecraft carried a boom-mounted vector fluxgate magnetometer that returned highly sensitive and accurate measurements of the geomagnetic field. These data allow, for the first time, the separation of temporal and spatial variations in field-aligned current (FAC) perturbations measured in low-Earth orbit on time scales of ~ 10 sec to 10 min. The constellation measurements are used to directly determine field-aligned current sheet motion, thickness and current density. In doing so, we demonstrate two multi-point methods for the inference of FAC current density that have not previously been possible in low-Earth orbit; 1) the "standard method," based upon s/c velocity, but corrected for FAC current sheet motion, and 2) the "gradiometer method" which uses simultaneous magnetic field measurements at two points with known separation. Future studies will apply these methods to the entire ST-5 data set and expand to include geomagnetic field gradient analyses as well as field-aligned and ionospheric currents.

1. Introduction

Space Technology 5 (ST-5) is the fifth mission in the New Millennium Program (NMP) and NASA's technology pathfinder for future micro-satellite constellation missions. ST-5 has three top level technology validation objectives: 1) Design, develop, and operate three full service micro-satellites, each with a mass less than 25 kg; 2) Demonstrate the ability of these micro-satellites to return research-grade magnetic field measurements; and 3) Operate the 3 satellites as a single constellation rather than as individual elements. The official NMP technologies validated by ST-5 include Miniature communications transponder, Cold gas micro-thruster, Variable emittance coatings, CMOS ultra-low power radiation tolerant logic, Low voltage power subsystem including Li-ion battery, and Autonomous ground operations. Further information on the ST-5 technology payload can be found in Carlisle et al. [2006].

The ST-5 spacecraft (s/c) were launched by a Pegasus into a dawn – dusk, 105.6 deg inclination, 300 x 4500 km orbit with a period of 136 min on 22 March 2006. The ST-5 spacecraft were spin-stabilized with periods near 3 seconds. Spin axis orientation for each s/c was typically maintained to be within 0.5 deg of ecliptic normal (excluding tests and maneuvers) with knowledge of ~ 0.1 deg. As shown in Figure 1a, the satellites were maintained in a "pearls on a sting" constellation. Multi-point measurements of field-aligned currents, ionospheric currents, ULF waves and pulsations, and crustal magnetic fields were obtained with the miniature tri-axial fluxgate magnetometers (MAG) carried by each of the three s/c.

Figure 1b displays the history of the spacing between the lead (#155) and middle (#094) and middle and trailing (#224) s/c in red and blue, respectively. As shown, these spacings varied between from just over 5000 km down to under 50 km. Inter-s/c spacing was controlled using cold gas propulsion system with an after-the-fact knowledge of ~ ±1 km. Conservative estimates of uncertainty in s/c absolute position knowledge varied over the course of the mission due to maneuvers and the amount of tracking, but they were typically ~1 to 5 km [M.

Concha, private communication, 2007]. Following completion of their 90 day mission, the ST-5 spacecraft were turned off and decommissioned on 21 June 2006.

In this study we provide a first look at the ST-5 multipoint magnetic field measurements and use them to determine FAC current sheet motion, thickness and current density without resorting to the usual single-s/c assumptions: 1) zero current sheet speed relative to the Earth; and 2) negligible contributions from waves and time-varying distant current systems.

2. ST-5 Magnetic Field Measurements

The ST-5 magnetometers (MAG) were developed at UCLA. These instruments function as "state vector machines" that deliver 16 vectors per second to the spacecraft command and data handling system. Each MAG sensor has dimensions of 5 cm x 5 cm x 3 cm and the total mass per s/c, including electronics, is approximately 600 gm. These instruments have two ranges: +/- 64,000 and +/- 16,000 nT that are controlled by the individual s/c using the measured magnetic field strength. The digital resolution of the MAG is 1.25 nT and 0.30 nT, respectively, in its high and low field ranges. The intrinsic noise for these miniature magnetometers was < 0.1 nT rms at 1 Hz. The MAG sensor, one per s/c, is mounted at the end of a stiff, very low mass, self-deploying boom. This boom places the sensor 110 cm from the center of the 53 cm diameter s/c to reduce the effects of any stray magnetic fields. Pre-launch testing in the Goddard Space Flight Center Magnetic Coil Facility showed that stray magnetic fields due to the satellite at the MAG sensor are < ~1 nT. The MAG data processing is described in the companion article by Wang et al. [this issue, 2007]. Based upon spin tone analysis and comparison against the International Geomagnetic Reference Field (IGRF) [Macmilan and

Maus, 2005], the ST-5 magnetic field measurements are of very high quality. The instrument gains and offsets changed by less than 0.1% over the course of the mission and no evidence of contamination due to stray s/c magnetic fields has been found [Slavin, 2006].

3. Field-Aligned Current Density Calculation Corrected for Current Sheet Motion

ST-5 ground tracks and magnetic field observations (1 sec averages) taken on 15 June 2006 are displayed in Figure 2a and b, respectively. The polar coordinate for the orbit display is magnetic local time (MLT) and the radial coordinate is magnetic co-latitude (MLAT) where 90 deg is the magnetic pole. As shown, three s/c as they crossed the northern polar auroral regions moving from dusk to dawn at altitudes of ~ 300 to 900 km. The magnetic field measurements are displayed in Solar Magnetic (SM) coordinates after subtraction of the background geomagnetic field using IGRF. In this coordinate system the X_{sm} axis lies in the plane defined by the Sun and the geomagnetic dipole and is perpendicular to the Earth's magnetic dipole (positive sunward), the Y_{sm} axis is perpendicular to the Sun – dipole plane and positive toward dusk, and the Z_{sm} axis completes this right-handed system.

As shown in Figure 2b, the ST-5 magnetic filed measurements exhibit the expected magnetic perturbations associated with Region 1 (R1) and 2 (R2) field-aligned currents [Iijima and Potemra, 1976; Sugiura, 1984]. The individual magnetic field traces are offset in time from each other by ~ 13 – 18 sec due to the separations of 142 km (start) to 133 km (end) between s/c #155 and #094 and 109 km (start) to 103 km (end) between #094 and #224. For this pass the FACs were nearly "steady" with close agreement between the magnetic fields measured at all three s/c. Finally, it should be noted that, after IGRF model field subtraction, the residual of the ST-5 magnetic field intensity is typically near zero. The one exception that is seen throughout the data set occurs when FAC encounters take place at altitudes below ~ 400 km such as from 17:37 - :41 in Figure 2b. During such intervals the horizontal ionospheric currents that close the R1 and R2 current sheets can be easily measured by ST-5. These ionospheric currents may add or subtract to the total magnetic field, depending upon the local time of the pass as previously observed by MAGSAT [Zanetti et al., 1984].

To apply the standard method for calculating current density from single s/c magnetic field profiles across FACs [Iijima and Potemra, 1976; Sugiura, 1984; Luhr et al., 1994; Anderson et al., 2000], the background magnetic field must first be subtracted using the IGRF model. The residual fields are then rotated into local geomagnetic coordinates, where the B_{zm} is along the IGRF field direction, B_{xm} is eastward and orthogonal to B_{zm}, and B_{ym} completes the right-handed system. The magnetic field perturbations in the B_{xm} are then attributed to a stationary, infinite current sheet that is traversed as a result of s/c velocity component in the Y_m direction, V_{scym}. The FAC current density is then just:

$$J_z = (-1/\mu_o)(\partial B_{xm}/\partial t)(1/V_{scym}) \qquad (1)$$

The ST-5 constellation allows us to relax the assumption that the current sheet be stationary by directly inferring its speed. The FAC velocity component in the Y_{sm} direction, V_{csy}, is equal to the observed change in current sheet location observed from one ST-5 s/c encounter to the next divided by the time between the encounters [see Wang et al., this issue, 2007]. The FAC current density J_z corrected for the motion of the current sheet is then:

$$J_z = (-1/\mu_o)(\partial B_{xm}/\partial t)[1/(V_{scym} - V_{csy})] \qquad (2)$$

Examples of ST-5 magnetic field measurements during over-flights of the auroral oval are shown in Figure 3a and b. The three components of the magnetic field are displayed in SM coordinates after subtraction of the IGRF model and time shifting the data to align the s/c #155 and #224 measurements with those from s/c #094. The FAC current densities, calculated using Eq. (2), are displayed in the bottom panel with a color key for each of the ST-5 satellites. The accuracy of the current density calculated in this manner is typically a few percent due to the high accuracy of the magnetic field measurements and the current sheet speed determination [see Wang et al., this issue, 2007]. Vertical dotted lines and labels indicate the intervals of Region 1 (R1) and Region 2 (R2) current.

Figure 3a shows a ST-5 pass over the southern auroral zone on 4 April 2006. The separations between s/c #094 and #155 and #094 and #224 were 2072 km and 303 km, respectively. The speed of these current sheets, as derived from the locations and times of the encounters with the ST-5 s/c was 0.15 km/s (equatorward). The thicknesses of the Region 1 and 2 currents were L_{R1} = 1009 km and L_{R2} = 698 km, respectively. After shifting the three magnetic field traces in time, there is very close agreement for all three components and the current density indicating that little or no temporal variations were present on timescales of several tens to several hundreds of seconds between the ST-5 encounters.

An auroral oval crossing two days later on 6 April 2006 with larger temporal variations is shown in Figure 3b. The separations between s/c #094 and #155 and s/c #094 and #224 were 2542 and 377 km, respectively. The speed and thicknesses for the current sheets derived from the times shifts are 0.57 km/s (equatorward) and L_{R1} = 281 km and L_{R2} = 615 km, respectively. During the ~ 7 min between the leading (#155-magenta) and trailing (#224) s/c the amplitude of the B_{ysm} perturbation grew by a factor of ~ 3. The changes observed between the other two s/c pairs on time scales of ~ 1 min to 6 min were smaller, but still very significant. In fact, the number and phase of the peaks in the magnetic perturbations and current density profiles measured at the 3 s/c are not the same and simple time shifts cannot allow even all of the larger features to be tracked from one s/c to the next. Additional studies of the ST-5 magnetic field observations will be necessary to quantify the amount and causes for the great variability seen in FAC current density often observed by ST-5 on time scales of 10 s to 10 min [see Le et al. and Wang et al., this issue, 2007].

4. Gradiometer Analysis of Field-Aligned Current Density

The ST-5 pearls-on-a-string constellation also allows the calculation of magnetic field gradients in low Earth orbit by differencing the magnetic field and satellite location data sets. The FAC current density is then equal to the measured gradient in B_{xm} in the Y_m direction, measured at s/c i and j, divided by the s/c separation normal to the current sheet:

$$J_z = (-1/\mu_o)(B_{scixm} - B_{scjxm})[1/(Y_{scim} - Y_{scjm})] \qquad (3)$$

The measurement of current using gradiometry has been pioneered by the Cluster mission with its 4 s/c in high altitude magnetospheric orbits [Balogh et al., 1997]. However, ST-5 is the first mission to provide the necessary measurements to support magnetic gradiometry in low Earth orbit. Errors in the determination of current density in this manner are estimated to be only on the order of a few per cent due to the high accuracy of the magnetic field measurements and ±1 km knowledge of the s/c separations. The determination of current density directly from gradient measurements in this manner has the virtue of rejecting aliasing due to temporal variations that have a wavelength comparable to or greater than the separation between the satellites (e.g., Alfven waves). These temporal variations are measured simultaneously both s/c and removed when the magnetic fields at the individual s/c are differenced to compute the gradients. In contrast, the customary inference of FAC current density from a single s/c requires not only that the current sheet be assumed planar, infinite, and stationary, but, to be rigorously correct, there should also be no contributions from waves or temporally varying distant current systems. The only other proven method for separating the contributions from "d.c." currents from those due to Alfven waves is to correlate the electric and magnetic field perturbations and use the E/B ratio to differentiate between these two the current sources [Sugiura, 1984; Ishii et al., 1992].

Examples of FAC current density determined using the gradiometric technique are displayed in Figure 4 a and b. For the 15 June 2006 auroral oval crossing the 094 – 155 and 094 – 224 s/c separations were 131 and 100 km, respectively. The FACs were determined to be moving poleward at 0.24 km/s and the thicknesses of the R1 and R2 intervals were 524 and 442 km, respectively. Similarly, for the 20 June 2006 event in Figure 4b, the 094 – 155 and 094 – 224 separations were 49 and 92 km, respectively. The FACs in this instance were determined to be moving poleward at 0.08 km/s and the thicknesses of the R1 and R2 intervals were 176 and 223 km, respectively.

For both auroral oval passes in Figure 4 the FAC current density calculated using the gradiometer technique, Eq. 3, for the 094 – 155 and 094 – 224 pairs is displayed alongside the motion corrected single s/c current density, Eq. 2, derived from the middle s/c, #094, data. Because the gradiometer technique is not sensitive to changes in the current density that occur on time scales shorter than the corresponding s/c separations divided by their orbital speeds, we have used lower resolution 12 s averages of the magnetic field at s/c #094 to calculate current density for this comparison.

For the 15 June 2006 interval, there is close agreement between the current density computed from the leading - middle and middle - trailing s/c pairs and the single s/c current density from #094. Furthermore, the single s/c current density from s/c #094 tends to lie intermediate between the gradiometer current density determinations by the leading and trailing s/c pairs. Hence, we conclude that for this interval the FACs were very stable over a time span of several minutes. Furthermore, the upper limit on the contributions of Alfven waves and variations in external currents to the single s/c current density derived from s/c #094 was less than 10%.

The 20 June 2006 auroral oval crossing is more complex. Despite the very close spacing of the ST-5 formation, there are differences of up to factor of 2 differences between the peak current densities determined from leading and trailing s/c pairs. Furthermore, the differences in the current profiles determined by the two s/c pairs are sufficient to prevent their close alignment using a single time shift. It should also be noted that the single s/c current density determination from #094 agrees well with the values determined by the trailing s/c pair. This strongly suggests that not only that FACs were very steady during the passage of the middle and trailing s/c, but also that there was little or no contribution to the single s/c current density due to wave activity or changes in distant current systems. Hence, despite the fact that the lead s/c, #155, was only ~ 10 s ahead of the middle s/c, #094, it is concluded that large, up to 50%, changes in current density took place during this brief interval. Additional applications of the gradiometer technique to the determination of FAC current density are planned for the future using this unique data set.

5. Summary

The ST-5 micro-satellite constellation has allowed, for the first time, the direct measurement of FAC motion, thickness, and current density in low Earth orbit on temporal scales of 10 s to 10 min. This paper used the ST-5 magnetometer to make the first gradiometric measurements of FAC current density in low Earth orbit and conduct an initial assessment of their temporal variability. Companion papers by Le et al. [this issue, 2007] examines the temporal variability of auroral FACs during a magnetic storm, Wang et al. [this issue, 2007] determine the statistical distribution of FAC motion and intensity, Rajaram et al. [this issue, 2007] present the first multi-point magnetic pulsation observations from low-Earth orbit, Huang et al. [this issue, 2007] compare ST-5 magnetic field measurements against a theoretical model of high latitude FACs, and Purucker et al. [this issue, 2007] utilize ST-5 gradiometer measurements near perigee to derive improved lithospheric magnetic and thermal models. Deployed in greater numbers by future science missions, micro-satellite constellations may open new doors for understanding and modeling ionospheric electrodynamics and geomagnetism.

Acknowledgments. We thank the all of the people who came together to make Space Technology - 5 mission a success. Computational assistance and data visual support provided by C. Liebrecht is also gratefully acknowledged.

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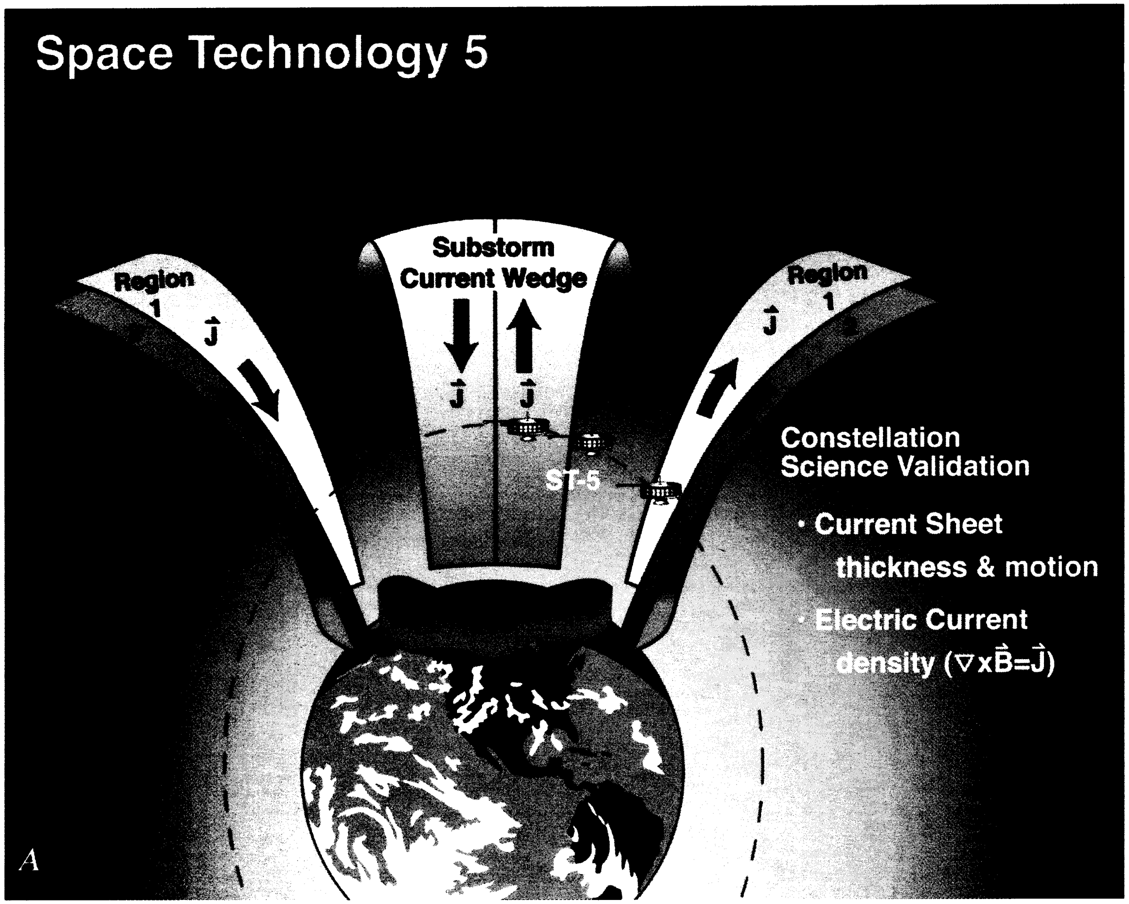
Figure 1. A) Illustration of the ST-5 orbit relative to the Region 1 and 2 and substorm current wedge field-aligned current sheets (N.B. dayside cusp currents are not shown). B) The achieved separations between the s/c are over the duration of the mission are displayed.

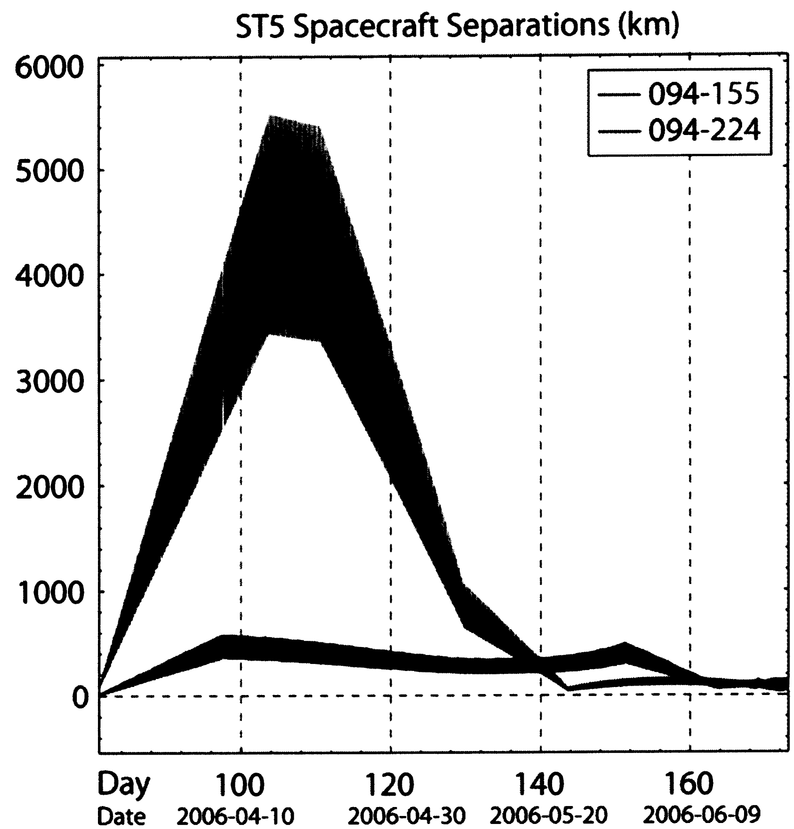
Figure 2. A) The ground tracks of the three ST-5 micro-satellites are displayed in MLT and MLAT for a northern polar pass on 15 June 2006. The lead s/c is #155 (red), the middle s/c is #094 (black) and the trailing s/c is #224 (blue). The magnetic field measurements (1 sec

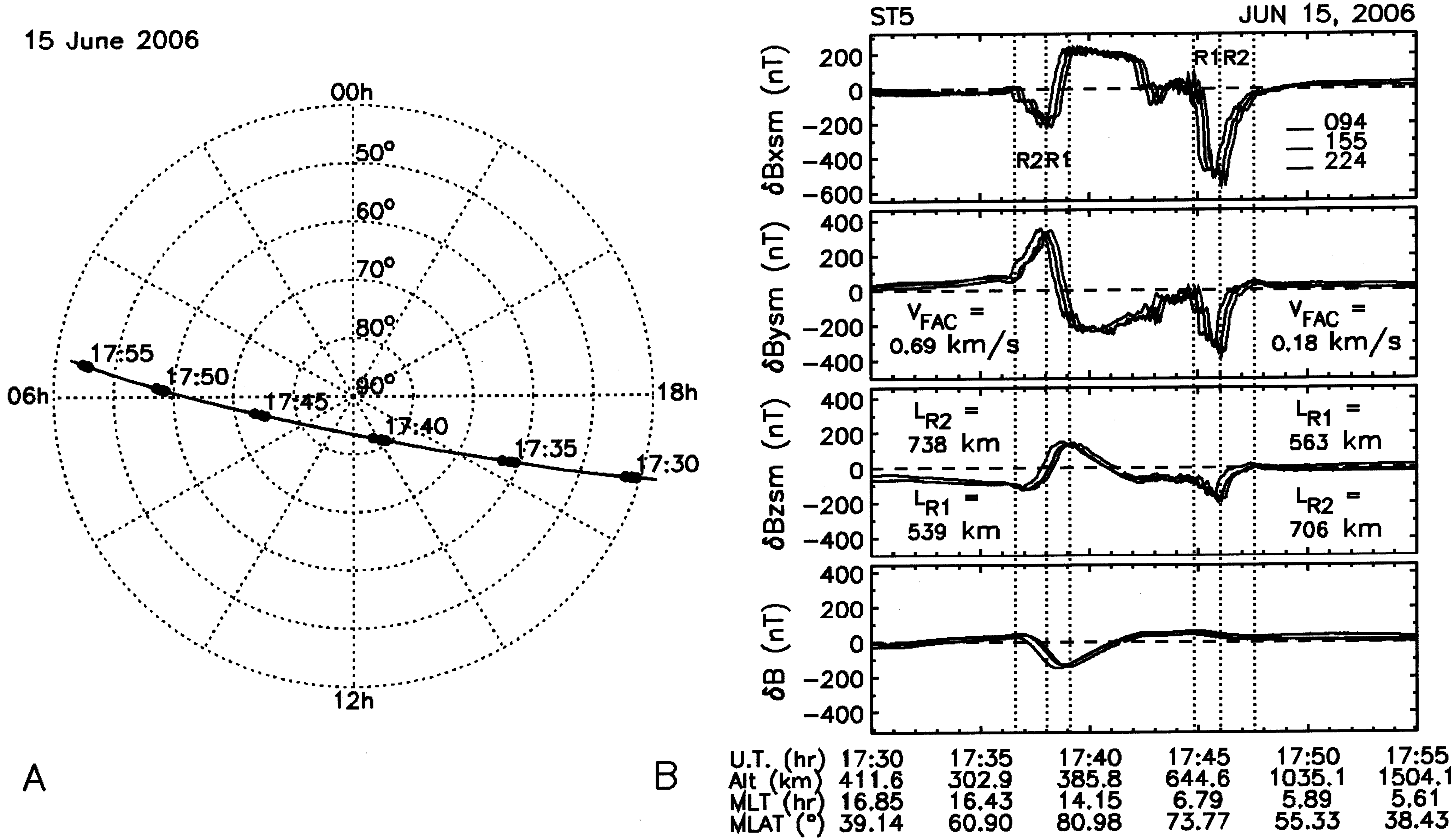
averages) from the ST-5 micro-satellites are displayed in SM coordinates after subtraction of the background geomagnetic field using IGRF.

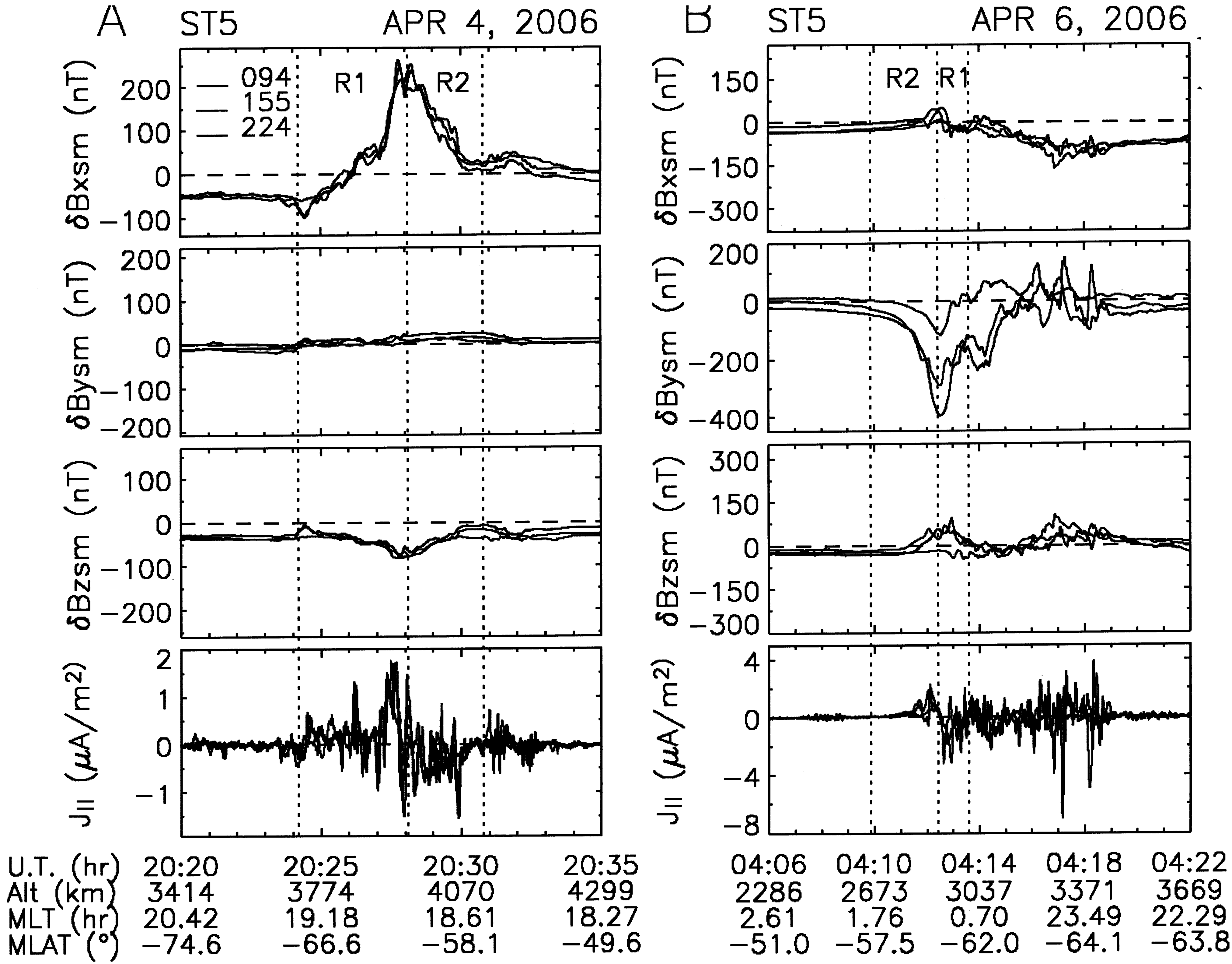
Figure 3. Magnetic field measurements (1 sec averages) from the ST-5 micro-satellites are displayed in SM coordinates after subtraction of the background geomagnetic field using IGRF along with single s/c determinations of FAC current density for auroral oval passes on A) 4 April 2006, and B) 6 April 2006. N.B., the magnetic field data in all panels have been shifted in time to align them with s/c 094.

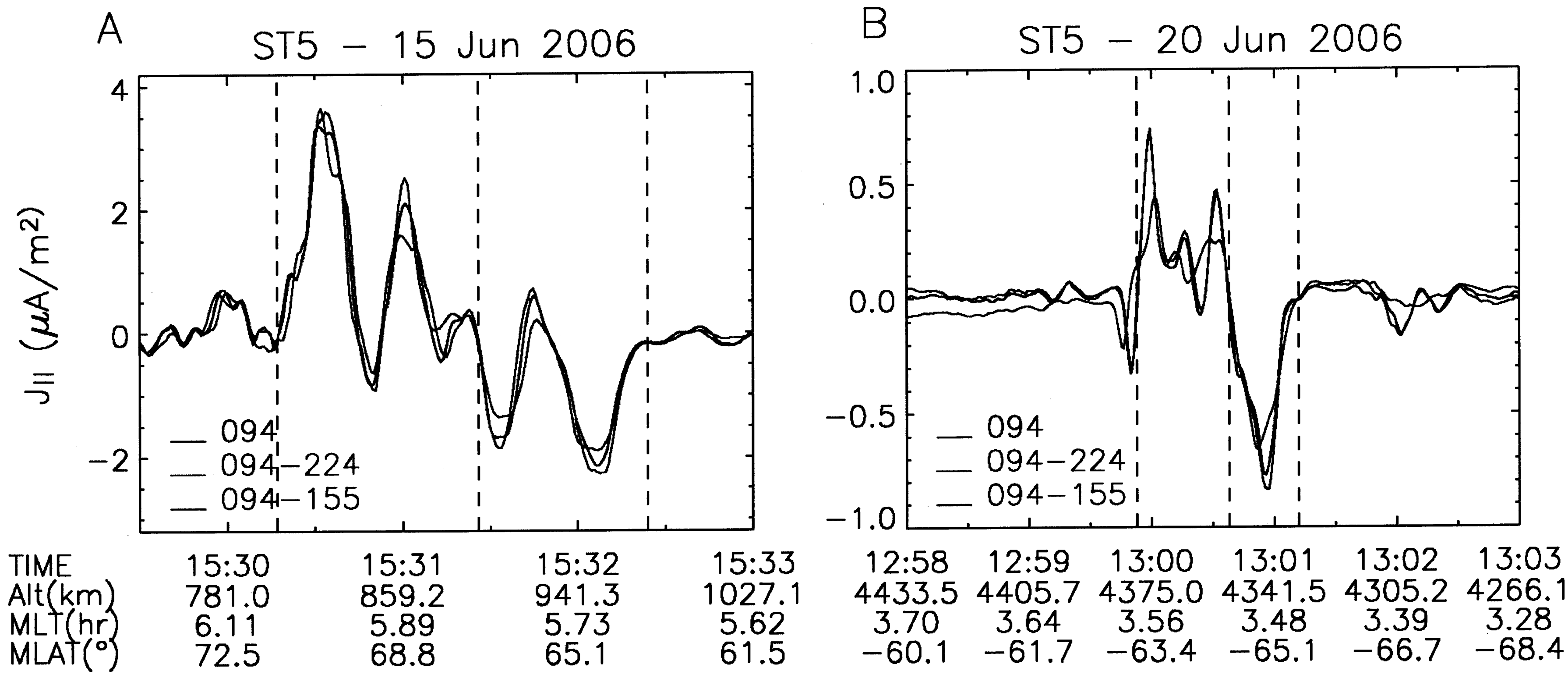
Figure 4. Field-aligned current density determined by differencing the magnetic field measured by s/c 094 and 155 (red) and s/c 094 and 224 (green) for A) 15 June 2006 and B) 20 June 2006. The traditional single satellite FAC current density determination applied to 12 s averaged data from s/c 094 is also displayed. N.B., the traces in both panels have been shifted in time to temporally align them with s/c 094.


Space Technology 5
Region 1
Substorm Current Wedge
Region 1
ST-5
Constellation Science Validation
• Current Sheet thickness & motion
• Electric Current density (∇xB=J)
A


ST5 Spacecraft Separations (km)
094-155
094-224
6000
5000
4000
3000
2000
1000
0
Day 100 120 140 160
Date 2006-04-10 2006-04-30 2006-05-20 2006-06-09
B


15 June 2006
00h
06h
12h
18h
50°
60°
70°
80°
90°
17:30
17:35
17:40
17:45
17:50
17:55
A
B
ST5
JUN 15, 2006
δBxsm (nT)
δBysm (nT)
δBzsm (nT)
δB (nT)
R2R1
R1R2
094
155
224
V_{FAC} = 0.69 km/s
V_{FAC} = 0.18 km/s
L_{R2} = 738 km
L_{R1} = 539 km
L_{R1} = 563 km
L_{R2} = 706 km
U.T. (hr) 17:30 17:35 17:40 17:45 17:50 17:55
Alt (km) 411.6 302.9 385.8 644.6 1035.1 1504.1
MLT (hr) 16.85 16.43 14.15 6.79 5.89 5.61
MLAT (°) 39.14 60.90 80.98 73.77 55.33 38.43


A
ST5
APR 4, 2006
094
155
224
R1
R2
δBxsm (nT)
δBysm (nT)
δBzsm (nT)
J|| (μA/m2)
B
ST5
APR 6, 2006
U.T. (hr) 20:20 20:25 20:30 20:35
Alt (km) 3414 3774 4070 4299
MLT (hr) 20.42 19.18 18.61 18.27
MLAT (°) −74.6 −66.6 −58.1 −49.6
04:06 04:10 04:14 04:18 04:22
2286 2673 3037 3371 3669
2.61 1.76 0.70 23.49 22.29
−51.0 −57.5 −62.0 −64.1 −63.8


A
ST5 – 15 Jun 2006
$J_{||}$ (μA/m^2)
094
094–224
094–155
TIME 15:30 15:31 15:32 15:33
Alt(km) 781.0 859.2 941.3 1027.1
MLT(hr) 6.11 5.89 5.73 5.62
MLAT(°) 72.5 68.8 65.1 61.5
B
ST5 – 20 Jun 2006
094
094–224
094–155
12:58 12:59 13:00 13:01 13:02 13:03
4433.5 4405.7 4375.0 4341.5 4305.2 4266.1
3.70 3.64 3.56 3.48 3.39 3.28
−60.1 −61.7 −63.4 −65.1 −66.7 −68.4