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Determination of substorm onset timing and location using the THEMIS ground based observatories

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[1] The NASA THEMIS mission is studying substorms by timing the substorm signatures at multiple satellite locations in the magnetosphere and in the aurora using 20 ground based observatories (GBO-s). The time resolution requirement is ~10 sec. The GBO-s provide a near contiguous array over North America. Each contains an all sky imager (3 s exposure cadence) and a magnetometer (with 2 Hz sampling rate). In one example substorm, the onset brightening of the equatorward arc was a gradual process (>27 seconds) with minimal morphology changes until the arc break up. The break up was timed to the nearest frame (<3 sec) and occurred at 58°N latitude and 256 ± 3°E longitude geographic (67°N magnetic latitude 22.1 hours MLT). The brightening of the arc was accompanied by a slow increase of the westward electrojet but this was too gradual for accurate timing of the event. High pass filtered magnetic data showed some wave activity but with significant delay (~40 sec) after the arc break up. Similar break up occurred in Alaska ~10 minutes later highlighting the need for an array to distinguish prime onset.
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1. Introduction

[2] Our understanding of magnetospheric physics is far from complete without a clear explanation of the fundamentals of the substorm process. The onset of the most active substorm phase, the expansive phase, is characterized by a sudden increase in the brightness of a quiet arc near the midnight meridian and by subsequent rapid, l0–30 min [*Akasofu*, 1964] poleward motion of the arc. The simultaneous intensification of the ionospheric currents produces large magnetic bays [*Akasofu and Meng*, 1967] and characteristic signatures before and after onset [*Rostoker et al.*, 1980]. Currently substorm theories are dominated by two models: the near-Earth neutral line (NENL) model [*Baker et al.*, 1996] and the current disruption (CD) model [*Lui*, 1996]. The central issue is the cause-and- effect relationship between reconnection (~>20 Re down tail) and current disruption (<10 Re down tail). The substorm onset timeline should provide a common reference frame for organizing substorm onset phenomenology and thereby provide a resolution of this issue. Substorm research largely depends on the precise definition and the timing accuracy of the substorm onset used in various observations. *Liou et al.* [1999] compared and calibrated some well known substorm onset indicators (polar and mid-latitude magnetic bays, Pi2 micropulsations, field dipolarization and energetic particle injection at geosynch. altitude) against auroral breakup as determined with Polar UVI images. Virtually all methods other than global imaging suffer, because the timing derived from a local measurement depends on the spatial proximity of the substorm onset. *Liou et al.* [1999] showed that auroral breakups determined from global auroral images are the most reliable, or at least consistent, onset signatures. In their plate 2, they indicate that the best method of timing using POLAR UVI has a typical uncertainty of about 40 sec in determining the auroral substorm onset. This limitation probably stems from the cadence limit of the UVI imager which is determined by the exposure time necessary to produce UV images with sufficient signal to noise ratio. On the IMAGE spacecraft the imager could only view the Earth once per revolution therefore the time resolution was limited by the 2 minute rotation period of the satellite [*Mende et al.*, 2000]. For more precise timing accuracy it was necessary to use the visible wavelength range where the aurora produces more photons.

[3] The NASA Time History of Events and Macroscale Interactions during Substorms (THEMIS) project intends to answer questions regarding the location of the initial trigger instability of substorms. In order to infer the direction of propagation of the energy in the Earth's tail region THEMIS uses correlative observations from five identical satellites strategically positioned to register the timing and location of substorm signatures. The mission will distinguish between the inward (e.g. NENL = near earth neutral line) or outward (e.g. CD current disruption) propagation of the substorm trigger and determine the model that provides an appropriate description of substorm trigger and evolution. In the magnetotail region the Alfven speed can be as large as $V_a = 10^3$ km sec^{-1} consequently substorm effects propagate between regions from >20 Re to <10 Re in about one minute or less. Therefore the time resolution for distinguishing between the localized instabilities should be ~10 seconds. This defines the cadence of the THEMIS space and ground instrumentation.

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[4] To monitor substorm associated auroras 20 THEMIS Ground Based Observatories (GBO-s), were deployed to provide near contiguous coverage over North America each with an all sky imagers (ASI) and a magnetometer. The network of imagers took global scale image collages (mosaics) with 3 second cadence providing hitherto unprecedented spatial and temporal resolution. The GBO magnetometer data are sampled at 2 samples per second. Magnetometers were also used from the other Canadian and US networks.

[5] The THEMIS GBO-s provide a new view of the auroral regions and allow the unambiguous recognition of the temporal onset from ground based data. This paper describes a substorm that occurred on the 23rd of December 2006 using the THEMIS GBO-s and discusses the accuracy of determining the onset location and timing.

2. Observations

[6] The all sky imagers produce 256 $\times$ 256 pixel images. Each pixel corresponds to a small region on the “sky” and the location of the region can be calculated by a star calibrated transformation matrix between the pixel coordinates of the image and the zenith-azimuth angles of the corresponding region on the sky at 110 km altitude. Routine data processing is performed in a reverse manner starting with a 1024 $\times$ 512 pixel matrix that represents the output mosaic. For each pixel in the output mosaic the appropriate region on the sky over a particular station was found, and the auroral intensity of the region was inserted into the pixel. If there were overlapping observations from adjacent station then the mean of the intensities was taken. This mapping process is performed once and a look up table generated to allow subsequent rapid mapping of the entire station array.

[7] For comparison with the optical aurora the horizontal magnetic vector data was superimposed on the images (Figure 1). These are the magnetic deviation components produced by subtracting a quiet day (December 28, 2006) set from each and representing the horizontal components (B_x meridional and B_y east west or zonal) by the red vectors (Figure 1). A substorm mosaic movie was made from 06:17:00 to 06:30:00 UT for December 23, 2006 using optical data from 6 stations (SNKQ, GILL, FSMI, WHI, INUV and FYKN) (see auxiliary material[1]).

[8] Prior to onset the aurora was relatively stationary with an extended east west arc located relatively near the zenith at stations SNKQ, GILL, and FSMI. The sky clarity at WHIT was not good enough to assess the situation between FSMI and the Alaskan sector. The latter is clearly seen from the INUV and FYKN data. The arcs were also visible in the Alaskan sector. Another poleward arc system was most visible at FSMI. The B variations were minimal at most stations except those that were near the field of view of GILL and FSMI where the break up subsequently occurred. The magnitude was slowly increasing prior to and reaching $\sim$200 nT at break up. The deviation was mainly southward signifying a westward ionospheric Hall current. There was no eastward current anywhere in the region therefore the location of the Harang discontinuity could not be recognized.

[9] The first sign of substorm onset was that the equatorward arc began brightening at 6:18:21 UT with simultaneous increase in the westward current. The first morphological change occurred at 6:18:33 UT (Figure 1) when the arc appeared bifurcated at the eastern sector of the FSMI frame indicated by an arrow. Otherwise the morphology did not change significantly until the arc breakup at 6:18:48 UT, unlike the onset observation of *Donovan et al.* [2006] who found that the auroral brightening was preceded by east west structuring. Note that Donovan et al. had only single station ASI observations and were unable to rule out a non-local onset and the propagation of the disturbance from outside of their field of view. In our case the break up occurred at latitude 58°N and longitude 256°E (67°N magnetic and 22.1 hours MLT) near the region of the bifurcation and 27 sec later than the first discernable brightening. Because the aurora is an east west elongated arc the onset determination is accurate to the nearest degree in latitude but the longitude could be in error of 2 to 3 degrees.

[10] The 6:19:36 UT image (Figure 1) shows a significant poleward auroral surge. Superimposed on the image is a rectangle showing oppositely directed magnetic field vectors at two adjacent stations. Counter flowing (north south) ionospheric currents could cause such a configuration. However in this case the scenario is consistent with the superposition of the B field from a vertical field aligned current (FAC) due to the substorm current wedge [*Akasofu*, 1972; *McPherron et al.*, 1973]. In fact the overall distribution of the magnetic variations (06:19:36 UT Figure 1) is consistent with a model of a current system consisting of a westward flowing electrojet current, a vertical upward flowing 500 A FAC centered to the west (61°N, 250°W) and a similar magnitude down going FAC to the east (60°N, 268°W) of the onset point. The image at 6:26:57 UT shows a situation where the aurora shows the pre-onset arc in Alaska just prior to its undergoing break up 5 minutes later. Subsequent to this image the aurora underwent a similar break up in Alaska with electrojet current intensification and a westward turning of field signature. This illustrates that the large local time coverage of the multiple GBO stations was needed to correctly identify that the prior onset location was in Canada. In general the widespread westward turnings of the horizontal B vectors after onset can be associated with an upward FAC poleward of the stations. This shows that the propagating breakup produced a similar upward flowing current in the Alaska sector but some minutes later.

3. Discussion and Conclusions

[11] The substorm onset was defined by *Akasofu* [1964] as the brightening of the equatorward arc and in our example this took 27 seconds, which would be too long a period for a time marker to satisfy the THEMIS timing requirements. Fortunately the arc break up was much more sudden and could be timed with 3 second accuracy, with the THEMIS ASI array. The break up of the aurora occurred at a bifurcation in the equatorward arc. This bifurcation became noticeable only a few frames prior to break up when the aurora gradually intensified. Other than this

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL030850.

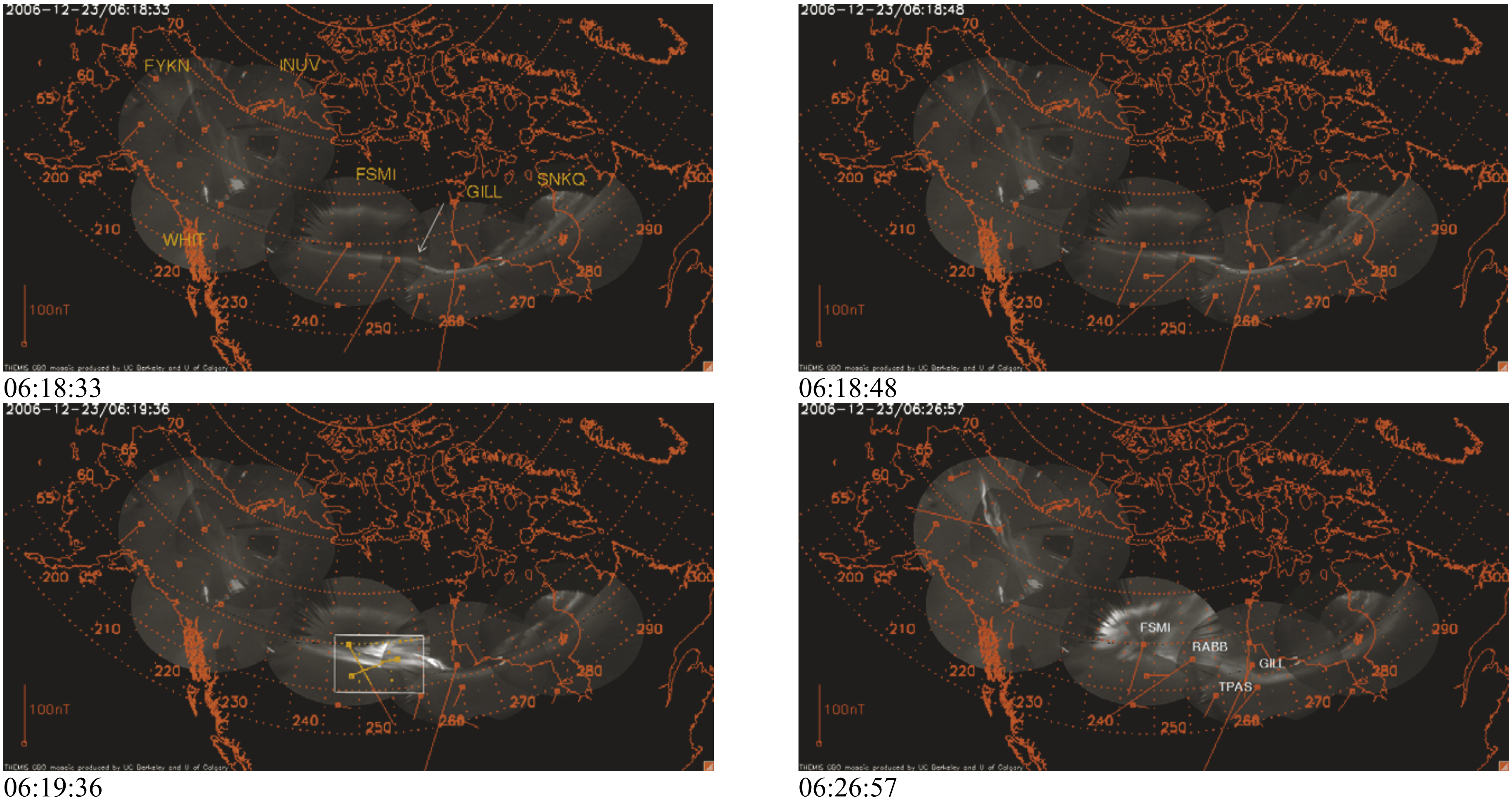

Figure 1. Mosaic presentation of six auroral images from the THEMIS GBO chain. The stations are SNKQ, GILL, FSMI, WHIT, INUV and FYKN. The magnetic field vectors were superimposed in the manner described in the text. The times of the images are indicated on the top left: 6:18:33 UT, bifurcation of the arc; 6:18:48 UT, first frame when the arc is structured prior to breakup; 6:19:36 UT, break up in progress field vectors are east-west and west-east because of strong FAC east and west of break up; 6:26:57, UT apparent substorm onset intensification seen in Alaska. Magnetic stations for Figure 2 are labeled blue.

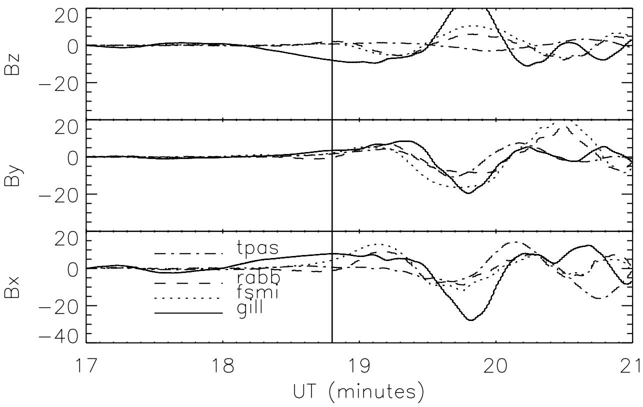

Figure 2. High pass filtered magnetic field variations from 4 stations. Vertical bar is the time of the auroral break up as established from ASI data.

bifurcation the aurora showed no wavelike structuring reported by *Donovan et al.* [2006]. During the initial arc brightening the intensification of the B variations was gradual. The largest intensification took place after break up. In order to examine wave like B field fluctuation, in Figure 2 we have plotted the high pass filtered (20 sec time constant) B field components for four stations (RABB, TPAS, FSMI, GILL) nearest to the break up. Significant magnetic impulses in the Pi2 frequency range occurred, but with a significant (~40 sec) delay. Magnetic pulsations of Pi2 type (40–150 s) are frequently observed during substorm periods and have long been considered as a reliable substorm onset signature [*Rostoker*, 1967; *Saito*, 1969]. The long periods associated with these type pulsations limit their timing accuracy.

[12] The concept of the substorm current wedge [*Akasofu*, 1972; *McPherron et al.*, 1973] suggests that after substorm onset a strong east west shunt currents develops through the ionosphere driven by the dawn to dusk electric convection field. This current should be a dissipative Pederson current through the ionosphere. Our modeling shows that indeed a strong field aligned current wedge is formed soon after onset. The ionospheric portion of the current is likely to be a Hall current [*Boström*, 1964; *Lui and Kamide*, 2003; *Akasofu*, 2003]. We expected that the substorm onset would be located near the Harang discontinuity [*Bristow et al.*, 2001] but we have seen no evidence of an eastward current in the vicinity of the onset region and the entire substorm was dominated by westward ionospheric currents.

[13] The event discussed here showed the THEMIS GBO all sky array was capable of timing the auroral break up to the nearest 3 seconds. This accuracy will be adequate for the THEMIS substorm timing objectives and is considerably better than the timing accuracy of the UVI images on POLAR [*Liou et al.*, 1999]. Other methods such as the timing of the polar region negative bays are also limited because of the slowness of the initial current increase. Presumably the formation and build up of the field aligned currents and the corresponding increase in the electrojet current is much less sudden. The filtered magnetometer data shows pulsations in the Pi-2 range but they start up with a significant delay after break up. Due to the limited space here the timing correlation of this event with other space based measurements was not included.

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