Temporal changes of surface wave velocity associated with major Sumatra earthquakes from ambient noise correlation

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Edited by John Vidale, University of Washington, and accepted by the Editorial Board June 15, 2009 (received for review February 4, 2009)

Detecting temporal changes of the medium associated with major earthquakes has implications for understanding earthquake genesis. Here we report temporal changes of surface wave velocity over a large area associated with 3 major Sumatra earthquakes in 2004, 2005, and 2007. We use ambient noise correlation to retrieve empirical Green’s function (EGF) of surface waves between stations. Because the process is completely repeatable, the technique is powerful in detecting possible temporal change of medium. We find that 1 excellent station pair (PSI in Indonesia and CHTO in Thailand) shows significant time shifts (up to 1.44 s) after the 2004 and 2005 events in the Rayleigh waves at 10–20 s but not in the Love waves, suggesting that the Rayleigh time shifts are not from clock error. The time shifts are frequency dependent with the largest shifts at the period band of 11–16 s. We also observe an unusual excursion ~1 month before the 2004 event. We obtain a total of 17 pairs for June, 2007 to June, 2008, which allow us to examine the temporal and spatial variation of the time shifts. We observed strong anomalies (up to 0.68 s) near the epicenter after the 2007 event, but not in the region further away from the source or before the event or 3 months after the event. The observations are interpreted as stress changes and subsequent relaxation in upper-mid crust in the immediate vicinity of the rupture and the broad area near the fault zone.

Earthquake occurrence involves stress accumulation and sudden releasing of stored energy. Monitoring possible temporal changes of the medium before and after a major earthquake has been a long-sought goal for understanding earthquake genesis, recurrence, and prediction. Laboratory studies have long indicated stress-dependent elastic properties from microfracturing (e.g., ref. 1). However, because such a temporal change is likely small and the Earth structure is very heterogeneous, great care must be taken in this endeavor. Previous effort has relied on similar waveforms produced by repeated sources from earthquakes (e.g., refs. 2 and 3) or controlled sources (e.g., refs. 4 and 5). Because repeated sources are not regular in time or space, the application to monitoring has great limitations. Recent progress in passive imaging with random noise offers an alternative (e.g., reviewed in ref. 6).

Ambient noise has been widely used to retrieve empirical Green’s function (EGF) of surface wave between stations (7, 8). The method involves cross correlation of continuous data for long enough time series. One major feature of ambient noise correlation is that the whole process is completely repeatable with different time segments, naturally producing EGFs with similar waveforms. Thus, the process makes it possible to continuously monitor the temporal evolution of the seismic wave velocity of the medium by tracking the time shifts of the EGFs.

The potential of this method has been shown by some recent studies. Sens-Schonfelder and Wegler (9) detected strong seasonal variation at Merapi Volcano, Indonesia from precipitation. Wegler and Sens-Schonfelder (10) detected a sudden drop in seismic velocity of 0.6% with the occurrence of Mw 6.6 Niigata, Japan earthquake from the autocorrelation of a station near the source. Brenguier et al. (11) reported precursory signals of less than 0.1% velocity variations before volcanic eruptions on La Réunion Island.

In this paper, we examine the 3 largest earthquakes in Sumatra, Indonesia in recent years (Fig. 1), occurring on December 26, 2004 (Mw = 9.1); March 28, 2005 (Mw = 8.6); and September 12, 2007 (Mw = 8.5), respectively (magnitude from Global CMT solutions). The fault rupture length ranges from 450 km (2007 event) to 1,200 km (2004 event) (refs. 12–14 and http://earthquake.usgs.gov/regional/world/historical.php). By comparing inter-station EGFs, we observed clear temporal changes in surface wave velocities after the earthquakes over a large area.

Results

Sumatra 2004 and 2005 Events. The available stations for 2004 and 2005 in the region are limited. We found 1 station pair, PSI in Indonesia and CHTO in Thailand, which has consistently high signal to noise ratio (SNR) in the EGFs for all of the months (Fig. 2). We examine time shifts (relative to reference EGF) of both Rayleigh wave (from cross correlation of vertical component) (Fig. 3a) and Love wave (from cross correlation of tangential component) (Fig. 3b) between PSI and CHTO. Detailed data processing is given below. The Love wave is very stable; throughout the whole time period, the time shifts are all within ±0.5 s with the average and the standard deviation of −0.09 s and 0.17 s, respectively. For most time periods, the Rayleigh wave is also stable with the time shifts ranging from about −0.5 s to 0.5 s; the average and standard deviation are −0.09 s and 0.25 s, respectively, for the months that exclude the period from December, 2004 to April, 2005. However, we observe significant time shifts around the time of 2004 and 2005 events in the Rayleigh waves (Fig. 3a). The largest shifts are for the months right after the events. The shifts are 1.06 s and 1.44 s for the month right after the 2004 event and 2005 event, respectively. These values are 4.6 and 6.1 times the standard deviation away from the average of the other periods. The time shifts are clearly visible from the EGF waveforms (Fig. 2). In addition, there is a small DC shift between the data from May 2005 to 2008 and the data before the 2004 and 2005 events (Figs. 2 and 3a).

The fact that the time shifts of the Rayleigh wave during the whole time period that excludes the event months are very stable and are of the same amplitude as the time shifts of the Love wave suggests that the anomalous behavior right after the 2004 and 2005 events is unlikely to be random. Similarly, we found no evidence of any sudden change of ambient noise sources by inspecting the amplitudes and waveforms of the positive and negative parts of the EGF waveforms.

Author contributions: Z.X. and X.S. designed research, performed research, contributed new reagents/analytic tools, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. J.V. is a guest editor invited by the Editorial Board.

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This article contains supporting information online at www.pnas.org/cgi/content/full/0901164106/DCSupplemental.

www.pnas.org/cgi/doi/10.1073/pnas.0901164106
negative delay parts of the inter-station correlations over calendar months (Fig. S1). To reinforce this conclusion, we show another example from a station pair (HIA and MDJ in northeastern China) far away from Sumatra (Fig. 3C). The pair also has consistently excellent Rayleigh-wave EGFs for all of the months. The time shifts range from $-0.5$ s to $0.5$ s for all of the months with the average and standard deviation of $-0.02$ s and $0.17$ s, respectively. Overall, the time shifts show very similar scatter to the Love and Rayleigh waves of the CHTO-PSI pair outside the 2004 and 2005 event months, but no significant time shifts occurred in the 2004 and 2005 event months for the HIA-MDJ pair.

One problem may be clock error. A relative clock shift between the 2 stations will result in a time shift in the EGF from the ambient noise correlation. Clock errors can be examined using positive and negative delay in the EGF correlation (15). However, our EGFs are highly asymmetric. We thus compare time shifts of Rayleigh waves and Love waves. Because the horizontal components and the vertical component use the same clock for the same station, a clock error would affect the EGFs of both Rayleigh and Love waves. In addition, the time shifts appear frequency-dependent (see below), which cannot be caused by a clock error. Thus, clock errors can be ruled out as the cause for the large time shifts in the Rayleigh wave of CHTO-PSI during the time periods of the 2004 and 2005 event from the lack of similar shifts in the Love wave.

It is also noticeable that CHTO-PSI pair does not show significant time shift after September, 2007 event. This may be explained by the distance dependence of the media velocity change. Significant time shifts are observed in pairs closest to this event as described below. The 2007 event is further to the south thus the impact of media velocity change to CHTO-PSI pair is smaller. Moreover, the distance dependence may also account

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**Fig. 1.** Map showing the location of the 3 major Sumatra earthquakes (stars) and seismic stations used in this study (triangles). Lines indicate the station pairs that we have time shift measurements. The black thick line is the pair CHTO-PSI for the 2004 and 2005 events, and the thin lines are the pairs used for the 2007 event. Arrows represent the rupture direction of the earthquakes. Rupture areas are simplified from previous studies (refs. 12–14 and http://earthquake.usgs.gov/regional/world/historical.php).

**Fig. 2.** Rayleigh waves of the station pair CHTO-PSI from ambient noise correlation for the period from May, 2004 to December, 2005. Each trace corresponds to 1 month of stack. All of the traces have high SNRs, and the waveforms from different months are highly similar. The enlarged view in the right shows clear time shifts in the months of December, 2004 to June, 2006. The difference between the reference line (solid) and the dashed line indicates the relative shift between traces.

**Fig. 3.** Time shifts of various station pairs, relative to reference stack of all time periods. (A–C) Rayleigh wave for CHTO-PSI from vertical (Z) component correlation (A), Love wave for CHTO-PSI from tangential (T) component correlation (B), and a stable reference pair HIA-MDJ outside Sumatra region in northeastern China (C). Black open squares correspond to time shift in different calendar months. Every data point is put in the middle of that month. In A, 2 additional points were calculated using 1 month of data before and after the 2004 and 2005 events that exclude the event dates. Gray dashed lines in CHTO-PSI ZZ and TT plots indicate the time period from January, 2006 to August, 2006 when no data are available. Solid diamond with error bar indicates the average time shift ± 2 standard deviations for all of the time periods except 2 months after the 3 Sumatra events. Arrows mark the dates of the 2004 and 2005 events. (D) Enlarged view of time shifts of CHTO-PSI Rayleigh wave before December, 2004 event, showing a weaker but significant precursory signal. Dashed line indicates the average time shift in the period before 2004 event. Two solid lines mark the 2 standard deviations from the average. The time shift (open circle) are associated with a Rayleigh wave that is calculated using every 30 days before the 2004 events (rather than using the calendar months). The time shift is plotted at the middle of each time period. The trend curve at the end uses measurements from A that contain a mixture of data before and after the events.
for the larger shift after the 2005 event, relative to that after 2004 event, even though the 2004 event has a larger magnitude.

We conclude that the large time shifts in Rayleigh wave after the 2004 and 2005 events are the result of temporal change of the velocity of the medium associated with these major earthquakes.

**Sumatra 2007 Event.** More stations are available in this region for the 2007 event with the addition of stations in Indonesia and Malaysia. To enhance SNR and to obtain more pairs, we compute the EGFs using 2 consecutive months of data with a moving step of 1 month. We calculate EGFs for all possible station pairs and obtain 17 pairs with good SNR for all time segments between June, 2007 and June, 2008 (Fig. 1).

We observe clear time shifts after the earthquake for some pairs. The pairs related to the station MNAI closest to the epicenter show largest time shifts. There are 3 pairs related to MNAI for the September, 2007 event, i.e., KOM, PMBI, PSI, SBM, and UGM; the largest time shifts for these pairs are $-0.26\,\text{s}$, $-0.43\,\text{s}$, $-0.22\,\text{s}$, and $-0.77\,\text{s}$, respectively. The pair closest to the epicenter of the 2007 event (MNAI-PMBI) shows the largest time shift ($1.36\,\text{s}$), which occurred in the period of October–November, 2007 (Fig. 4). The largest time shifts for all of the other pairs occurred in the period of November–December, 2007 (the time shift for MNAI-PMBI in this period is $0.84\,\text{s}$).

The number of station pairs allows us to construct the pattern of time shifts for each time period by spatial averaging and to examine how the spatial pattern changes with time. We use a moving window of $10^\circ$ by $10^\circ$ in longitude and latitude and a step of $2^\circ$ in longitude or latitude direction in the averaging. If there are 3 stations inside the window, we calculate the root mean squares (rms) of the time shifts for all of the pairs associated with the stations inside the window and find the averaged latitude and longitude of these stations. This rms value is then taken as the time shift at the averaged latitude and longitude for that time period. We perform the same spatial averaging for each time period and thus, construct a time evolution of the spatial pattern of the time shifts. Maps of the spatial pattern for a few months before and after the event are shown in Fig. 5, and Movie S1 shows the time evolution. It is important to stress that because we have carefully selected our station pairs so that each station pair selected has consistently good EGFs that allow us to measure the time shifts of each pair for all of the time periods, the spatial averaging has the same station-pair distribution and the same ray path coverage for all of the time periods. This data selection is important in eliminating any bias from nonuniform distribution of station pairs on the temporal evolution.

The rms values are small (less than $0.27\,\text{s}$) for the periods up to the period of July–August, 2007. However, strong anomalous signals appear after the earthquake. The strongest anomaly (up to $0.68\,\text{s}$) in the averages is near the epicenter, but the anomalies also appear $500$ to $1,000\,\text{km}$ away from the epicenter. The signals disappear further away from the source. The anomalies die away $\approx 3$ months after the earthquake, and no significant anomalies are observed in any location after that. The evolution of the spatial pattern and the coincidence of both the location of the anomalies and the time when the anomalies emerge suggest strongly that the temporal changes are associated with the 2007 earthquake. In this interpretation, the earthquake caused changes in medium velocity over a large area near the source for a few months after the earthquake, resulting in the observed temporal changes in the Rayleigh wave travel times.

**Conclusion and Discussion**

We observe clear travel time shifts of Rayleigh wave in the months after the 2004, 2005, and 2007 major Sumatra earthquakes from ambient noise correlation. The absence of anomaly in Love wave suggests the Rayleigh wave anomaly is not from clock error. High SNR and similar waveforms of the EGFs for different periods ensure the accuracy of the measurements of the time shifts. The stability of the background measurements suggests the significance of the anomalous time shifts. The locations and emerging times of the anomalies coincide with the 3 major events. Therefore, we conclude that the travel time anomalies of Rayleigh wave are from the temporal change of surface wave velocity from a change of medium velocity after the major earthquakes.

The discrepancy between the Rayleigh and Love waves is intriguing. Because Rayleigh wave is sensitive to deeper structure than Love wave at the same period, 1 possibility is that the temporal change occurs at depths below the Love wave sensitivity. We examine this issue by determining whether the time shift is frequency dependent. To increase the SNR for the frequency analysis, we stacked correlation of CHTO-PSI in the 2 months right after 2004 and 2005 events. We filter the stacked
correlation with 7 different period bands (5–10 s, 7–12 s, 9–14 s, 11–16 s, 13–18 s, 15–20 s, and 17–22 s, respectively). We measure the relative time shift with respect to the reference EGF for each period band. Because the surface wave is dispersive, we carefully select different time windows for different periods to include all of the surface wave energy (Fig. 6A). Our measurements show that the time shift increases and then decreases with period with the maximum shifts at 11–16 s (Fig. 6B). Measurements using 1 month of data after the 2004 and 2005 events, respectively, confirm the trend, although the SNR is not as good at marginal periods. The depth region of maximum sensitivity of fundamental Rayleigh wave varies from 10 to 30 km for period 10–20 s, which is in agreement with the depth range of maximum slips of 2 events (14). However, fundamental Love wave for this period range is sensitive to shallower structure (maximum sensitivity less than approximately 10 km). This depth dependence of the media velocity change can account, at least partly, for the discrepancy between the Rayleigh and Love waves, particularly if the media change is concentrated within small depth range of maximum rupture, for example. Alternatively, the medium velocity change may be anisotropic, resulting in different behaviors of Rayleigh and Love waves. More data are needed to sort out precisely the nature and the location of the media change.

Our observed temporal changes are from station pairs separated by several hundreds to 1,000 km and from 10–20 s surface waves sampling the depth of upper-mid crust (10–20 km), indicating a large-scale disturbance of the medium beyond the rupture areas. The 3 events are thrust events with small dip angles dipping toward the Sumatra coast. The imaging of the rupture areas (14) and the aftershock activities indicate that the west most stations are near the edge of the ruptures (PSI to 2004 and 2005 events and MNAI to 2007 event) and all of the station pairs are away from the rupture areas. The observed velocity change of the medium seems complex. Both positive and negative time shifts are observed after the 2007 event when several station pairs are available. There is no obvious correlation between the length of the path and the amplitude of time shift. Thus, the medium velocity can increase or decrease. The fluctuation by season is more sensitive than approximately 10 km. This depth dependence of the media velocity change can account, at least partly, for the discrepancy between the Rayleigh and Love waves, particularly if the media change is concentrated within small depth range of maximum rupture, for example. Alternatively, the medium velocity change may be anisotropic, resulting in different behaviors of Rayleigh and Love waves. More data are needed to sort out precisely the nature and the location of the media change.

Mechanisms that have been proposed for temporal changes of seismic velocity include (i) stress-induced changes of fault zone properties at seismogenic depth (3, 5, 10, 16), (ii) damages from fault zone rupture and subsequent healing (4, 17), (iii) damages of shallow crust from strong-ground shaking (18, 19), and (iv) rapid changes in ground water near the surface (9) or fluid activities in shallow crust (20). The depth sensitivity of the observed Rayleigh wave temporal changes suggests that surface or shallow crust effects (mechanisms 3 or 4) can be ruled out. As our station pairs are far away from the earthquake rupture areas, we also argue that the temporal changes are not directly related to the rupture damages or other properties within the fault zones. The most plausible explanation is stress changes associated with the major earthquakes and subsequent relaxation. The stress changes can be observed not only in the immediate vicinity of the rupture area but also several hundreds of km away from the source region. Interestingly, the ‘‘DC’’ residual time shifts (Figs. 2 and 3A) after the 2004 and 2005 events, relative to those before the events (with an average of 0.06 s from April–October, 2004), may be part of the long-term stress relaxation (16). On the annual base from May through April, the average time shift has generally decreased from 0.00 and 0.10 s in 2005–2007 (with a data gap from January–August, 2006) to −0.06 s, −0.21 s in 2007–2009 (with measurements extended to April, 2009). A longer-term monitoring is required to confirm the trend.

There appears a significant excursion before the 2004 event in the CHTO-PSI pair (Fig. 3C). To examine the stability of the time-shift measurements, we construct EGFs for a moving window of 1 month and a moving step of 10 days for the period 10–20 s. The curve decreases a little and then increases sharply after the event (December 26, 2004).

The above statistics are affected by the limited duration of observations before the 2004 event. Of particular concern are seasonal variations in time shifts, such as those found by ref. 10, where velocity perturbations were found to correlate with precipitation and thus, can be explained by seasonal variation of underground water. However, at periods 10–20 s, our Rayleigh waves are not sensitive to superficial conditions. If we compare variations of time shifts from year to year, there is no seasonal signal (Fig. S2). There are, however, short-term excursions from all of the months at which we have looked (April, 2004 through April, 2009, excluding the months where there are no data and those of Sumatra earthquakes January–April, 2005), among which the November 2004 anomaly is the largest. If we compare each month with the previous 6 months where there are measurements, we can find 3 strongest excursions (November, 2004 departing by 4.2σ, January, 2007 by 3.7σ, and March, 2008 by 3.1σ). In November and early December, 2006, there was only 1 magnitude >7 event (November 11, 2004, Timor Region, Mw 7.5, Lat. −7.87°, Long. 125.12°). The event is too far away from CHTO-PSI path to cause observable signals. We conclude that the anomaly before the 2004 event is unusual, but we cannot rule out that it is a random excursion.

Our observations of large-scale disturbances in medium velocity before and after a major earthquake need to be confirmed...
with a denser network around the source region. Recent large earthquakes with dense instrumentation nearby (such as 2008 Wenchuan, China; 2002 Denali, Alaska; and 1999 Chi Chi, Taiwan) provide a fertile ground for testing. The large-scale disturbance observed in this study suggests the stress-induced change in elastic properties is not just concentrated in the fault-zone area, making it easier to observe. If a precursor of media velocity change is observable over a large area, it has direct application for earthquake prediction.

Data Processing

We requested 54 months of long period continuous data (January, 2004 to June, 2008) for stations in the Southeast Asia region (Fig. 1) from Incorporated Research Institutions for Seismology Data Management Center (IRIS DMC). The stations are operated by GSN, Malaysia, Japan, and China. We retrieve inter-station EGFs using a computer program (with some modification) from Michael Ritzwoller’s group, described in details by Bensen et al. (21). We filter the raw data between 4 to 50 s. For each of the Sumatra events, we exclude the data of the event date to eliminate the strong earthquake signals in the correlation. The EGFs obtained from the ambient noise correlation for almost all station pairs are not symmetric between the positive time delay and the negative time delay. Examples of ambient noise correlations are shown in Fig. S1 for the CHTO-PSI pair. The asymmetry indicates the noise sources are mostly from the south (Indian Ocean). Note the relative amplitude between the negative delay (containing Rayleigh wave EGF) and positive delay (mostly noise) is quite stable, suggesting no systematic or sudden change of the ambient noise source and that Rayleigh wave EGFs can be consistently retrieved. We use the symmetric part of the EGF by summing both the positive delay and negative delay parts, which enhances the SNR and stability of the EGF. We then filter the EGFs with a band pass filter between 10 and 20 s, where SNR is highest for most station pairs.

To examine temporal change, we obtain EGFs from short-time segments (e.g., 1 month) of continuous data. A reference EGF is constructed using all of the time periods. Only those pairs with consistent high SNR for each time segment throughout the whole time period were selected for analysis. We measure the time shift of the EGF from each time segment relative to the reference EGF using waveform cross correlation. As an example, Fig. 2 shows Rayleigh wave EGFs between stations PSI (in Indonesia) and CHTO (in Thailand). The waveforms are highly similar, making it possible to measure accurately relative time shifts. We typically use a large time window (~60 s) that includes the large portion of the surface wave packet in measuring the time shift with cross-correlation method. The sampling interval of the retrieved EGFs is 1 s (same as the raw data). We interpolate the EGFs to sampling interval of 0.01 s before using waveform cross-correlation to measure the relative time shifts.

One major source that could contaminate the noise-correlated EGFs is the intensive aftershock signals, even though normalizations in time and frequency domains have been applied to remove any energetic signals in the EGF construction (21). To test the effect of aftershocks, we compare EGFs using 1 month of data after the 2004 event and 1 month of data after the 2005 events with and without major aftershocks. Both months show significant positive time shifts as discussed above. We mute the records 1 min before expected arrivals and 1 h after the expected arrivals for all of the events with Mw 5.5 and above in our study region (10° S to 20° N and 90° E to 110° E). Because earthquakes with Mw 5.5 are quite common in this region and there is at least 1 event happening in almost every month, we determine that Mw 5.5 is a reasonable cut off to study the behavior of major aftershocks. We windowed out a total number of 41 and 24 aftershocks found in the time period from December 27, 2004 through January 25, 2005 and from March 29, 2005 through April 27, 2005, respectively. To avoid artificial spikes, the data windowing is done after filtering of the raw data and before the temporal normalization (21) and a cosine taper (width of 120 s) is used in the data windowing. About 95% and 97% of data are kept for noise correlation after windowing for the month after the 2004 event and the month after the 2005 event, respectively. The waveforms of EGFs before and after aftershock windowing, the waveforms are almost exactly identical with only a slight change in amplitudes (Fig. S3), indicating that the Green’s functions we retrieved are stable and the observed large time shifts after the 2004 and 2005 events are not likely from aftershocks.

Rayleigh wave can be retrieved from either correlation of vertical component (Z-Z) or correlation of radial component (R-R). The latter, however, is subject to error in instrument orientation (such as a lath). There is a long data break between December, 2005 and September, 2006 for PSI station and CHTO changes its orientation after September, 2006. Examination of Z-Z, R-R, and T-T noise correlations for the CHTO-PSI pair suggests that, while Z-Z and T-T correlations are generally consistent throughout the time period, the waveforms of R-R correlation are not consistent with a marked change after the data break (after September, 2006) (Fig. S4). Love wave energy leaked to R-R correlation to become the dominant energy after the data break, suggesting significant error in instrument orientation. Because Rayleigh wave arrives later than Love wave, it may be contaminated by the coda of Love wave. Therefore, we used Z-Z correlation, rather than R-R correlation, for Rayleigh waves in this study. Nevertheless, using Rayleigh waves from R-R correlation from April, 2004 to December, 2005, where the waveforms are generally consistent, we found significant time shifts (0.87 s and 1.76 s, respectively, relative to the average before October, 2004) after the 2004 and 2005 events that are generally consistent with the results from Z-Z correlation. On the other hand, Love waves from T-T correlation in the CHTO-PSI pair are more consistent which is similar to the Rayleigh wave; although there is also an apparent change in the coda of Love waves (Rayleigh wave energy) after the data break (Fig. S4B). The consistency of Love waveforms make it possible to measure accurately the time shifts as presented above.

ACKNOWLEDGMENTS. We thank 2 anonymous reviewers and the Editor for thoughtful reviews and suggestions, which greatly improved the quality of the paper. The Green functions were calculated using codes from Dr. Michael Ritzwoller’s group (with minor modifications). All of the data were downloaded from IRIS DMC. Most of the figures were plotted using GMT software (22). This work was supported by the National Science Foundation Grant EAR-0838188 and Air Force Research Lab Grant FA8718-07-C-0006.