Development and characterization of a nano-scale temperature sensor (T-NSTAP) for turbulent temperature measurements

This content has been downloaded from IOPscience. Please scroll down to see the full text.
(http://iopscience.iop.org/0957-0233/26/3/035103)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 128.112.36.193
This content was downloaded on 24/02/2015 at 21:39

Please note that terms and conditions apply.
Development and characterization of a nano-scale temperature sensor (T-NSTAP) for turbulent temperature measurements

Gilad Arwatz, Yuyang Fan, Carla Bahri and Marcus Hultmark

Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544-0710, USA

E-mail: garwatz@princeton.edu

Received 31 August 2014, revised 5 January 2015
Accepted for publication 7 January 2015
Published 2 February 2015

Abstract
A new nano-scale temperature sensor (T-NSTAP) is presented. The T-NSTAP is a sub-miniature, free-standing, platinum wire suspended between silicon supports, designed for temperature measurements at high frequencies. The new sensor is designed to have a bandwidth far superior to that of conventional cold-wires, which in combination with its small size, minimizes the effect of temporal and spatial filtering on the data. Unfiltered data allows for unique investigations of the scalar turbulence, including the dissipation range. Temperature measurements were conducted with the T-NSTAP in a heated grid-turbulence setup, with constant mean temperature gradient, and compared to data acquired with a conventional cold-wire. It is shown that the cold-wire signal is significantly attenuated over a broad range of frequencies, including lower frequencies. The attenuation has a direct and substantial effect on the measured variances and the estimated scalar rate of dissipation. The observed differences between the conventional cold-wire and the T-NSTAP are compared to what is predicted by a cold-wire model with convincing agreement over the entire spectrum. A close to perfect agreement between the two sensors is shown when the cold-wire data is corrected for end-conduction effects using the cold-wire model. In addition, a frequency content analysis of the probability density function of the temperature and its derivative is performed with direct comparison between the cold-wire and the T-NSTAP.

Keywords: cold-wire, NSTAP, temperature, grid turbulence, temporal filtering

(Some figures may appear in colour only in the online journal)
fluctuations, it is necessary to design a probe which has minimal end-conduction effects, yet is small enough to avoid spatial filtering. Several studies have shown that the dynamic response of the cold-wire includes not only the time constant related to the wire thermal-inertia, but also time constants associated with the stubs and prongs [1, 5–8]. These studies investigated the dynamic response in specially designed configurations such as heating by a laser beam or through theory, but were never verified in turbulent temperature measurements. Consequently, these models and deductions were not adopted by the turbulence community and therefore turbulent temperature measurements are still commonly acquired using cold-wires that are calibrated statically, and treated as a first order system. Until the development of the T-NSTAP, conventional cold-wire sensors offered the fastest available temporal response, and thus their true frequency response has not been accurately confirmed.

To design an improved sensor for temperature measurements, both the temporal and spatial resolution need to be taken into account. Since the attenuation due to both spatial and temporal filtering is Reynolds number dependent, the optimal design of such a sensor will vary among applications. Spatial filtering is governed by the ratio of the length of the wire and the smallest turbulent length scales in the flow. Thus, a wire that shows severe spatial filtering in one flow can be unaffected by spatial filtering in another. Consequently, minimizing spatial filtering is achieved by reducing the length of the sensing element, \( \ell \). A decreased length reduces the thermal mass of the wire filament, which is desired, but it also increases the end conduction effect with low-frequency attenuation as a result. These thermal effects and trade-offs are well known and captured in detail by the lumped parameter model proposed by Arwatz et al [2]. Since the design of the sensor relies on the model, a brief overview is presented. In this model (figure 1), the heat transfer rates are modeled with thermal resistors and heat accumulated in each element, namely the wire filament, stubs and prongs with thermal capacitors (denoted by subscripts 1, 2 and 3, respectively), while assuming the temperature to be constant in each of these parts.

Each element of a cold-wire (capacitor) is exposed to a heat flux (current going through a resistor), and therefore the model includes three series RC circuits in a parallel configuration. The elements are connected to each other and heat is conducted between adjacent elements represented by thermal contact resistance. The voltage on each node represents the temperature, and the resistances \( R_1 \), \( R_2 \) and \( R_3 \) correspond to the heat transferred to the wire, the stubs and the prongs, respectively. The three elements are coupled to each other through the contact resistances \( R_{12} \) and \( R_{23} \). Finally, the prongs conduct heat to the holder, an effect modeled by the resistance \( R_4 \), connecting the prongs to ground. After obtaining the characteristic heat transfer coefficient for each element (which depends on the heating configuration), a system of differential equations is obtained describing the temperature of each element by performing an energy balance at each node.

The resulting model predicts that end-conduction effects, due to heat transfer from the wire filament to the prongs through the stubs, affect both high and low frequencies. An important parameter is the roll-off frequency of the wire filament, \( f_1 \). The model shows that increasing the diameter has the undesirable effect of decreasing the roll-off frequency, and hence one faces a trade-off between maximizing amplitude and frequency. This trade-off is illustrated in figure 2(a), where multiple frequency and amplitude curves are shown for different diameters. It is further shown that the data is collapsed when plotted against \( \ell_1 d_1 / L d_2 \), where \( \ell_1 \) and \( d_1 \) are the wire filament length and diameter respectively, \( L \) is the distance between the prongs and \( d_2 \) is the stubs’ diameter. This figure clearly reveals the trade-offs between the design parameters of the cold-wire, which is very useful when designing an improved sensor.

The maximum amplitude that can be achieved for a specific probe is determined by the remaining elements, namely the prongs, the stubs and the interactions between them. The effect of the stubs is embedded in the results shown above since increasing the filament implies a decrease in the stub dimensions. Figure 2(b) illustrates the effect of prong dimensions and shows the amplitude as a function of prong length \( \ell_3 \) and diameter \( d_3 \). In order to minimize attenuation, \( \ell_3 d_3 \) should be minimized by reducing the length and increasing the cross-sectional area of the prongs.

These considerations led the authors to design a new temperature probe based on the model, almost an order of magnitude smaller, with increased roll-off frequency and reduced low frequency attenuation. The model was used to test the effect of varying different geometric and material properties on the frequency response. The new sensor closely follows the design of the nano-scaled thermal anemometry probe (NSTAP), recently developed at Princeton University. The NSTAP is manufactured using standard semiconductor fabrication techniques and its small size greatly reduces filtering in measurements of velocity fluctuation in high Reynolds number flows [9–11].

The new temperature probe (T-NSTAP) was used to measure turbulent temperature fluctuations in grid turbulence with an imposed linear mean temperature gradient. The data acquired with the new temperature sensor is compared to data acquired simultaneously using a conventional cold-wire.
Finally, the differences are compared to what is predicted by the cold-wire model described above.

2. Experimental setup

2.1. Sensor design and fabrication

The T-NSTAP is designed to have a wire length of 200 µm (considerably smaller than conventional cold-wires, yet more than three times longer than a regular NSTAP). The rectangular cross-section of the wire has a width of approximately 2 µm, and thickness of about 100 nm. The wire is patterned on a 100 nm diameter double-sided, polished, prime grade silicon wafer. To process the wafer, a 500 nm layer of silicon dioxide (SiO2) is first deposited onto one side of the wafer using plasma-enhanced chemical vapor deposition (PECVD) as an insulating layer as well as for structural support during the 3D etching of the sensor. Approximately 200 evenly-spaced T-NSTAP wires (the part inside the dashed box in figure 3(a)) are patterned using standard bilayer-resist photolithography. 100 nm of platinum (Pt) is then sputtered onto the patterned wafer with 10 nm of chromium (Cr) underneath acting as an adhesive layer. Platinum is selected as the material for the sensing element due to its relatively low thermal conductivity, ease of process, and the fact that it is not chemically reactive with the environment. The bilayer-resist ensures smooth wire edges after metal lift-off, which results in a faster etch rate inside the opening during the RIE process (RIE-lag) and therefore naturally forms a 3D slope from the base of the probe toward the sensing wire, as seen in figure 4(c).

Figure 2. (a) Roll-off frequency $f_1$ and measured amplitude $A_1$ as a function of $\ell_1 d_1/L d_2$, where $\ell_1$ and $d_1$ are the wire filament length and diameter respectively, $L$ is the distance between the prongs and $d_2$ is the stubs diameter. (b) Measured amplitude $A_1$ as a function of $\ell_3 d_2/L d_3$ where $\ell_3$ is the prongs’ length and $d_3$ is the prongs’ diameter.

Figure 3. T-NSTAP pattern design masks: (a) metal side of the probe includes the Pt wire and Au prongs. (b) Shape and dimension of the Au prongs. (c) Mask design for the backside of the probes. The size of the openings (shown as the white polygons in the enlarged view) is designed to be larger near the Pt wire and gradually decreases when closer to the base of the probe. This is because a larger opening will result in a faster etch rate inside the opening during the RIE process (RIE-lag) and therefore naturally forms a 3D slope from the base of the probe toward the sensing wire, as seen in figure 4(c).
the material being etched. This effect has been used to create 3D shapes with a 2D mask [12–15]. Therefore, the mask for the backside of the wafer is designed with varying opening sizes (figure 3(c)) to form a slope from the base of the probe towards the sensing wire, as seen in figure 4(c) after the deep reactive-ion etching process. At this stage, individual sensors are released from the wafer while another short RIE process is applied on the sensors to clean off silicon excess and to expose the sensing wires. Lastly, a wet etch is applied to remove the supporting oxide layer, and a T-NSTAP with a free-standing wire on the silicon support is formed (figure 4).

Besides the difference in wire dimensions, a major modification in the design of the new T-NSTAP compared to the regular NSTAP is the use of two different metals instead of a single layer of platinum. According to the cold-wire model [2], prongs with higher thermal conductivity are more desirable. Therefore, a two-layer design is adopted with 200 nm layer of gold on the prongs due to high thermal conductivity as compared to Pt. Additionally, as suggested by the model, the prongs were made shorter by 1 mm in order to reduce low-frequency attenuation.

The final design was chosen as a result of an iterative design to optimize the frequency response and minimize attenuation. In this process, the cold-wire model was used to evaluate the effect of different design parameters and an oscillating jet setup was used to compare the frequency response of various designs (figure 5).

In this setup, a rotating chopper wheel was set to alternate between a cold and a hot stream of air, producing a step in temperature. Figure 6(a) shows a characteristic cycle of the oscillations for two different design considerations, the first one being the regular NSTAP and the other the optimized T-NSTAP. In this case, the oscillations were set to 30 Hz, and even at this low frequency a significant difference in the amplitude can be seen between the two sensors. Additionally, a close look at the cycle reveals that the T-NSTAP exhibits a slightly faster response. These effects are better illustrated in the bode plot of figure 6(b). The oscillating jet setup has a complex dynamic behavior, as the chopper wheel cuts the air jet with a finite angular velocity (limiting the setup to frequencies below 1 kHz), which interferes with the temperature step response. In addition, a mixing process is added to the dynamics, making it impossible to decouple the step response from the system. However, this setup can still be used to compare the performance of different sensors, rather than extracting the exact frequency response of any given sensor. This approach, combined with predictions by the cold-wire model, was used to evaluate the actual frequency response of the sensors. Arwatz et al [2] determined the thermal contact resistances in the model empirically by using a chopped laser setup, and found that all tested sensors had similar values. For the remainder of this study those values will be used in the model for all sensors. Figure 6(b) shows a Bode plot of the predicted response of the regular NSTAP (designed for velocity measurements) and the T-NSTAP, as well as the ratio between the two sensors, both from experimental data and the model. The frequency response predicted by the model for both a regular NSTAP and a T-NSTAP is shown in figure 6(b).

A significant difference between the two sensors is clearly observed where the T-NSTAP performs better over the entire frequency range. In particular, the new temperature sensor exhibits substantially reduced attenuation at low frequencies due to the improvements made to the prongs and the longer wire filament, with a roll-off frequency greater than 10 kHz. Due to the complicated dynamics of the chopped jet setup, only ratios of bode plots can be considered. The experimental ratio agrees convincingly with that predicted by the model, giving further confidence in the model.

2.2. Wind tunnel experiment

The experiments were performed in an open loop wind tunnel at Cornell University, with a 9.1 m long test section, 0.91 m × 0.91 m cross-section, and a passive grid with mesh.
size $M = 2.54 \text{ cm}$. A detailed description of the experimental setup can be found in [16]. The mean temperature gradient was generated by 32 heated coils placed in a parallel array just upstream of the flow conditioning section. A conventional cold-wire, with 1.27 µm diameter and $\ell/d = 350$, and a T-NSTAP were mounted on a linear stage, and simultaneously measured the same flow conditions. Temperature fluctuation signals were low-pass filtered (cut-off frequency $f_c = 25 \text{ kHz}$) and digitized at a sampling rate of 50 kHz for 300–600 s. The cold-wire and T-NSTAP were operated using a constant current circuit with the current being 0.25 mA and 0.05 mA, respectively. The T-NSTAP and cold-wire were statically calibrated against a thermocouple by moving the probes in the cross-stream direction and taking advantage of the mean temperature gradient.

Measurements were taken with mean streamwise velocities $U$ of 6 m s$^{-1}$ and 9 m s$^{-1}$ for various positions downstream from the grid ($x/M$) and mean temperature gradients $\Gamma$ of 5 K m$^{-1}$ and 8 K m$^{-1}$, respectively. Previous investigations [16, 17] using the same setup verified that for these conditions, temperature behaves as a passive scalar. The Reynolds number $Re_x = \ell \nu / \nu$, where $\ell$ is the integral length scale, $\nu$ is the standard deviation of the velocity fluctuations and $\nu$ is the kinematic viscosity, ranged from 75 to 330 and 130 to 600 for $U = 6 \text{ m s}^{-1}$ and $U = 9 \text{ m s}^{-1}$, respectively. The Taylor Reynolds number $Re_\lambda = \lambda \nu / \nu$, where $\lambda$ is Taylor microscale, varied from 35 to 100 and 45 to 120, for $U = 6 \text{ m s}^{-1}$ and $U = 9 \text{ m s}^{-1}$, respectively.

3. Results

As mentioned in section 1, cold-wires traditionally offered the fastest available response and therefore have not been accurately characterized. The measurements presented in this section directly compare the frequency response of a conventional cold-wire with that of the T-NSTAP in turbulent flow conditions.

Figure 7 shows an example of 1D temperature spectra measured using both a cold-wire and a T-NSTAP, with a constant level of electronic noise subtracted. A clear difference between the two sensors can be seen. At first glance, the difference might seem small and of minor importance. However, a closer look at the inset of figure 7 plotted in semi-logarithmic scale reveals a significant difference between the two sensors. This attenuation might be a result of either spatial or temporal filtering. Spatial filtering is first assessed by considering the temperature obtained by averaging over the field in a volume around a point. The 1D spectrum $F_\theta(k)$ is obtained by integrating the 3D spectrum $\phi_\theta(\vec{k})$ over $k_2$ and $k_3$ as follows

\[ F_\theta(k) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \phi_\theta(\vec{k}) \mathcal{W}(\vec{k}) \, dk_2 \, dk_3 \]  \hspace{1cm} (1)

where $\mathcal{W}(\vec{k})$ is the averaging volume function around a parallelepiped representing the sensor. $W(\vec{k})$ is the Fourier transform of the product of three delta functions in the limit as the physical dimensions of the sensor go to zero.

For an isotropic flow, $\phi_\theta(\vec{k})$ is related to $E_\theta(k)$, the 3D spectrum around a sphere of radius $k$ by

\[ \phi_\theta(\vec{k}) = \frac{E_\theta(k)}{4\pi k^2} \]  \hspace{1cm} (2)

where $k^2 = k_2^2 + k_3^2 + k_3^2$.

If the probe is effectively a 1D line average in a direction perpendicular to the flow with length $l$, equation (1) reduces to:

\[ F_\theta(k) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_\theta(k) \left( \frac{\sin(k_3 l / 2)}{k_3 l / 2} \right) \, dk_2 \, dk_3 \]  \hspace{1cm} (3)

Applying equation (3) to the data with $E_\theta(k) = - k \, dF_\theta/dk$ reveals that, by considering the length of the cold-wire ($l = 0.4 \text{ mm}$), no visible difference in the spectrum is observed as compared to the spectrum obtained without the effect of spatial filtering. A more quantitative measure of this effect is obtained by looking at the variance, which is related to the 1D spectrum $F_\theta(k)$ by

\[ \frac{1}{2} \sigma^2 = \int_{0}^{\infty} F_\theta(k) \, dk \]  \hspace{1cm} (4)
The measured variance is within 1% of the variance corresponding to a zero length probe ($l = 0$) for all streamwise locations. Therefore, it is concluded that the spatial filtering is not the cause of the difference between the sensors observed in figure 4. This result is not surprising as the Batchelor scale is of the order of 0.5 mm compared to 0.4 mm for the cold-wire.

Considering temporal filtering, and as predicted by the cold-wire model, the cold-wire is significantly attenuated even at low frequencies. Traditionally, the cold-wire is modeled as a first order system which offers a relatively simple way to determine the cut-off frequency, and is used as a benchmark for the roll-off frequency in temperature fluctuation measurements. The attenuation at low wavenumbers, predicted by the cold-wire model [2] can be clearly observed in figure 7. This attenuation directly, and significantly, affects the measured variance, $\bar{\theta}^2$.

Figure 8(a) shows 1D temperature spectra for $x/M = 160$ and two different initial conditions ($6$ and $9$ m s$^{-1}$), measured using both sensors. The model presented in [2] was used to correct the cold-wire data. Specifically, by considering the properties and dimensions of the cold-wire used to acquire the data, a transfer function is deduced from the model. The inverse transfer function, in conjunction with a low-pass filter necessary to ensure stability of the system, is used to build a correction transfer function. By convolution of the measured signal with the correction transfer function, a corrected signal is obtained (indicated by the solid line in figure 8(a)). The corrected spectrum agrees remarkably well with the T-NSTAP data over all wavenumbers. A demonstration of the significant
effect of the low wavenumber attenuation, and the applicability
of the model, can be captured by considering the tempera-
ture variance shown in figure 8(b). A remarkable difference is
observed between the cold-wire and T-NSTAP data, where the
cold-wire data is attenuated by as much as 25% for both initial
conditions and over all streamwise positions. Furthermore, it
can be seen that the variance of the corrected signal agrees
well with the T-NSTAP measurements. Traditionally, at least
the low wavenumber data has been assumed to be accurate,
which implies that any filtering effects on the variances are
small. The observed difference in the low wavenumber regime
and the resulting variance sheds uncertainty on previous data
acquired with cold-wires.

Figure 9 shows a Bode plot of the ratio between the frequency response of
the cold-wire to the frequency response of the T-NSTAP for both
$U = 6 \text{ m s}^{-1}$ and $U = 9 \text{ m s}^{-1}$. Solid lines represent the behavior
obtained from the model while markers represent experimental data.

Figure 10 shows the dissipation spectra measured using both
a cold-wire and a T-NSTAP. In this representation, high fre-
quencies are amplified, as seen in equation (5). It can be seen
that the dissipation peak amplitude measured by the cold-wire
is attenuated by $\sim 50\%$ compared to the T-NSTAP. This has
a significant effect on the estimated scalar rate of dissipation
given by

$$
\epsilon_\theta = \int_0^\infty D_\theta(k) \, dk
$$

which is an important scaling parameter for scalar turbulence.
In the case presented in figure 10, $\epsilon_\theta$ obtained from the cold-
wire measurements is underestimated by $\sim 35\%$ compared
to the T-NSTAP measurements. The figure also presents
the cold-wire signal corrected by the model, which yields a
scalar rate of dissipation within $4\%$ of that measured by the
T-NSTAP. As previously indicated, the correction works well
at all frequencies and enables almost full recovery of the dis-
sipation peak. Due to the relatively large attenuation at higher
wavenumbers, and possible noise contamination, the roll-off
of the corrected dissipation spectra is not fully recovered. This
fact further emphasizes the need for improved sensors, such as
the T-NSTAP.

In recent years, more attention has been given to the pas-
sive scalar probability density function (pdf), which describes
all statistical moments. Specifically, the focus was the study
and analysis of the exponential tails evident in the tempera-
ture pdf, which are due to rare, large-amplitude fluctuations.
By developing a phenomenological model for a passive
scalar advected by turbulence, Pumir [18] showed that the
pdf exhibits exponential tails in the presence of a mean scalar
gradient. Kerstein [19] reached a similar result using a linear-
eddy model. Warhaft et al [20, 21] observed exponential tails
in the presence of a mean temperature gradient, as opposed
to the velocity pdf, which is of Gaussian nature. In addition,
the authors investigated the effect of filtering on the tails and
observed that the use of a high-pass filter to remove large-
scale effects helps in revealing the exponential tails. The
authors similarly observed an exponential form in the pdf of the temperature derivative. Figure 11(a) shows an example of the pdf of the derivative \( \partial \theta / \partial t \) for both the cold-wire and the T-NSTAP. The exponential tails can be clearly observed for both sensors, however, wider tails can be seen for the T-NSTAP data. Investigating the effect of the frequency response of the sensor for both the pdf and the pdf of the derivative was done by fitting the tails to an exponential form

\[
P(t) \sim e^{-\alpha t}
\]

where \( \alpha \) corresponds to the slope of the tails when plotted on a semi-logarithmic scale. Figure 11(b) presents a new technique to analyze the frequency content of the pdf. In particular, the figure shows the sensitivity of the tails to filtering for both the pdf and the pdf of the derivative \( \partial \theta / \partial t \). A band-pass filter with a 4 kHz low-pass cut-off was applied to the data acquired with both sensors while varying the high-pass filter. It was found that the low-pass filter has a negligible effect on the tails, whereas the cut-off frequency of the high-pass filter significantly affects the exponential form, as can be seen in the figure. Specifically, the exponent \( \alpha \) in equation (7) is a strong function of the filter setting. Note that for the given flow conditions and streamwise location, the integral scale corresponds to a frequency of 70 Hz while the dissipative scales are around 3 kHz. Inspection of the pdf reveals that both sensors exhibit similar behavior at cut-off frequencies below ~150 Hz, after which a major difference is observed. Increasing the high-pass cut-off frequency reduces the low frequency content of the signal while giving more weight to higher frequencies. The attenuation has widespread effects on most aspects of the measurements, including the measured variances. The attenuation seen in the temperature spectra measured by the cold-wire directly results in the variance being underestimated by at least 25%. High frequency attenuation significantly reduces the dissipation peak and the scalar rate of dissipation by as much as 35%. A significant difference in

4. Conclusions

A new fast-response, sub-miniature, temperature sensor (T-NSTAP) is developed, evaluated and compared to a conventional cold-wire. The design and manufacturing techniques for the T-NSTAP are based on those previously developed for the NSTAP, which has proven extremely successful in capturing small scale turbulence at high Reynolds numbers. The T-NSTAP was designed to reduce low frequency attenuation by using a lumped capacitance model previously developed for cold-wire attenuation [2], and as a result the T-NSTAP has different dimensions as well as a new dual metal-layer construction. It is shown that the T-NSTAP has a dramatically improved frequency response, and that the signal from a conventional cold-wire is severely attenuated even at frequencies as low as 10 Hz. It is further shown that temporal filtering and not spatial filtering is responsible for the observed attenuation. The attenuation has widespread effects on most aspects of the measurements, including the measured variances. The attenuation seen in the temperature spectra measured by the cold-wire directly results in the variance being underestimated by at least 25%. High frequency attenuation significantly reduces the dissipation peak and the scalar rate of dissipation by as much as 35%. A significant difference in
the pdf of the temperature signal and the pdf of its derivative between the cold-wire and the T-NSTAP is observed. A new technique to assess the frequency content of the tails of the pdf and the derivative pdf is applied, revealing that the difference is more pronounced with high-pass filtering and that the tails pertain to high frequency events. Overall, the attenuation in the cold-wire data is closely captured by the cold-wire model. However, it was shown that high amplitude intermittencies evident in the tails of the pdf could not be recovered, and therefore the correction by itself cannot fulfill the need for a new sensor.

Acknowledgments

The authors would like to thank Prof Z Warhaft for generously making his wind tunnel and laboratory resources available for measurements. We are also grateful to Prof W K George for his many helpful comments and suggestions for analyzing the data and helping in spatial filtering assessment. This work was made possible through the Fondation pour l’Etude des Eaux du Léman (FEEL) and the EPFL vice directorate office, particularly P Gillet. The development of the T-NSTAP is part of the international, interdisciplinary research project elemo (www.elemoch.ch) whose objective is to study and preserve freshwater habitats. Additional funding was received through ONR grants N00014-12-1-0875 and N00014-12-1-0962 (program manager K-H Kim).

References