NOTES AND CORRESPONDENCE

De-Aliasing of Large-Scale High-Frequency Barotropic Signals from Satellite Altimetry in the Japan/East Sea

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ABSTRACT

In the Japan/East Sea, energetic high-frequency large-scale barotropic motions are shown to lead to large aliasing errors in satellite altimetry observations. The combined aliasing from several neighboring and crossing tracks produces artificial mesoscale signals in altimeter-mapped products, significantly changing the map interpretation. The alias can be well suppressed by subtracting the large-scale barotropic motions observed by bottom pressure sensors. By using coastal tide gauge data in the Japan/East Sea, about 78% of the alias source variance can be removed, which offers an alternative way to suppress the alias for other time intervals without bottom pressure measurements.

1. Introduction

The existence of high-frequency energetic barotropic motions in the open ocean has been shown to lead to a large aliasing error in satellite altimetric observations (Stammer et al. 2000; Tierney et al. 2000). Gille and Hughes (2001) provided in situ support for model aliasing estimates by examining bottom pressure recorder measurements from a variety of locations in open oceans. Stammer et al. (2000) demonstrated that ocean general circulation models have considerable skill in predicting these motions. The water motions in semienclosed marginal seas are heavily influenced by their boundaries. The uncertainties of satellite altimetry data in a semienclosed sea may typically be double that of open oceans, partly because of lower accuracy in high-frequency signal corrections, such as tidal correction (Morimoto et al. 2000; Yanagi et al. 1997a,b). Morimoto et al. (2000) showed that the result of the harmonic analysis of tide gauge data is very useful for the tidal correction of altimetric data from satellites in the Japan/East Sea (JES).

Recent studies have found unique barotropic large-scale motions in marginal seas (Lyu and Kim 2005; Park and Watts 2005; Fukumori et al. 2007; Xu et al. 2007). For example, in the JES, Lyu and Kim (2005) found basinwide fluctuations of sea level associated with nearly uniform barotropic motions, which can be driven by atmospheric pressure over the JES, wind stress along the straits that connect the JES to the open ocean, and oceanic pressure differences along the straits caused by sea level changes outside the straits. In the Mediterranean Sea, Fukumori et al. (2007) found that more than 50% of the large-scale nontidal variance of sea level is attributable to a barotropic oscillation affecting the entire basin.

The large-scale nearly uniform barotropic changes in sea level in the JES, hereafter called the common mode, contain energetic high-frequency signals at periods <70 days, which account for about half of the total sea level rms amplitude (Xu 2006). Because 70 days is the European Remote Sensing satellite (ERS) Nyquist period, this suggests that aliasing from the common mode can seriously corrupt the altimeter measurements. Such high-frequency signals will also present a

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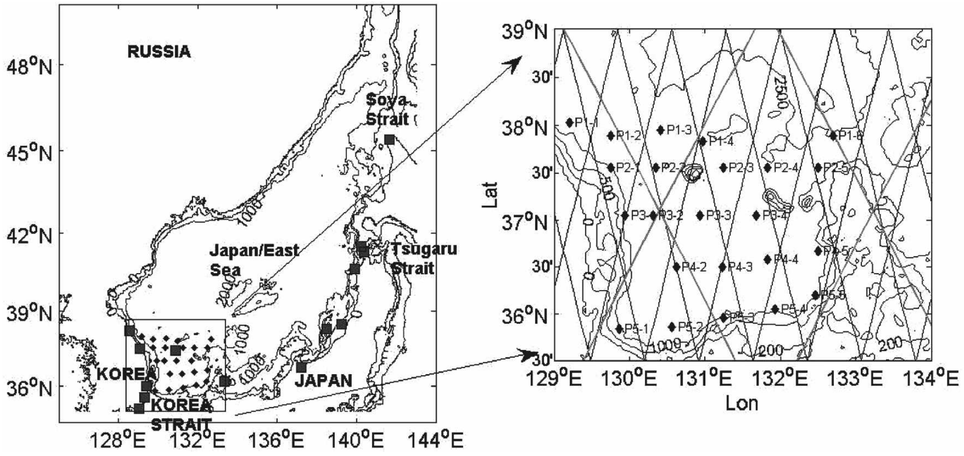

FIG. 1. The Japan/East Sea. Black diamonds and gray squares indicate PIES and tide gauge stations, respectively. The black and gray straight lines in the right panel indicate *ERS-2* and T/P ground tracks, respectively. The PIES site identification numbers Pn-m are shown. Bathymetry contours are in meters.

challenge to the interpretation of satellite data from the Gravity Recovery and Climate Experiment (GRACE), which promises to measure large-scale, long-period bottom pressure changes with an accuracy equivalent to better than 1 cm of water (Wahr et al. 1998). In the JES, Nam et al. (2004) illustrated the aliasing that arises from a Helmholtz-like sea level response to atmospheric pressure at periods of ~3–5 days (Lyu et al. 2002), which accounts for about 10% of the full common mode variance. However, the aliasing effect of the common mode does not seem to have been widely recognized even though it is potentially the largest source of aliasing error in this marginal sea.

In this study, we illustrate a spatiotemporal aliasing effect produced in satellite altimetry by the common mode. The common mode aliasing from neighboring and crossing tracks can mimic mesoscale signals, producing qualitatively artificial spatial features in synoptic mapping of a sea level anomaly (SLA). We will show how to suppress the common mode aliasing in satellite altimetry using bottom pressure (BP) or alternatively coastal tide gauge measurements.

2. Data

a. Bottom pressure and altimeter data

A two-dimensional array of pressure-recording inverted echo sounders (PIES) with 55–60-km spacing was deployed in the southwestern JES from June 1999 to July 2001 (Fig. 1). BP does not change when the sea level responds isostatically to atmospheric forcing. Thus, the BP measurements respond to nonisostatic barotropic variations and inherently require no inverted barometer (IB) correction. We first detided the hourly BP records accurately using the Munk and Cartwright (1966) tidal response analysis technique. Then we calculated the barotropic (nonsteric) contribution to sea level using the hydrostatic approximation. Park and Watts (2005) demonstrated almost perfectly uniform bottom pressure records at separations up to 250 km for a 2-yr period and argued that the SLA estimated from BP (BP SLA) within the Ulleung Basin could be used as a proxy for the common mode SLA throughout the JES. In our study, the average of the BP SLA is used as a proxy of the SLA common mode in the JES.

We used the AVISO *ERS-2* along-track SLA and the merged SLA products—the Ocean Topography Experiment (TOPEX)/Poseidon (T/P) and *ERS-2* (T/P + ERS-2)—produced by the CLS Space Oceanography Division. T/P and *ERS-2* data have a repeat period of 9.92 and 35 days, respectively. In addition to the standard corrections for tides, inverse barometer, radiometer, and electromagnetic bias, additional corrections involving subsampling, filtering, and longwave corrections had been made before the merging process (Ducet et al. 2000; SSALTO/DUACS 2001). To illustrate common mode aliasing and de-aliasing in altimeter observations, we use the along-track *ERS-2* data without the additional corrections. The distance of adjacent observation points is about 6.6 km along subsatellite ground tracks. The mapped SLA product was obtained from AVISO reprocessed T/P and *ERS-2* data, as described in detail in the SSALTO/DUACS User Handbook. The mapped data used in this paper have a 7-day temporal resolution and a 1/3° longitude Mercator grid spatial resolution.

b. Sampling issues

Figure 2 shows the large-scale common mode SLA time series from June 1999 to June 2001. Substantial

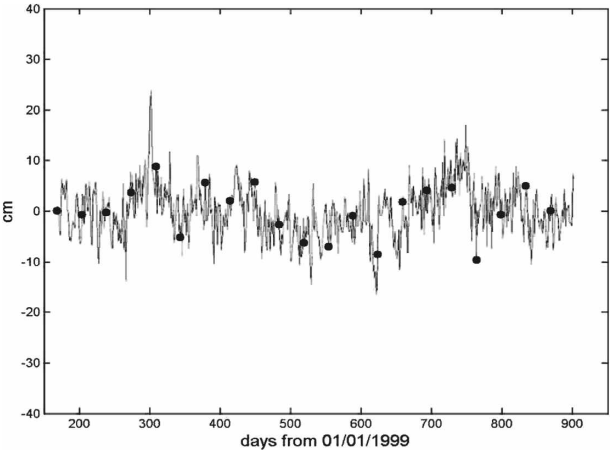

FIG. 2. Hourly common mode anomaly estimated from the BP measurements. The solid dots have an interval of 35 days (*ERS-2* sampling interval). The variability between the two adjacent solid dots exemplifies the aliased anomaly due to the inadequate sampling interval.

energy exists at all periods shorter than 70 days, and SLA changes of up to 20 cm occur within a few days. Note that *ERS-2* sampled the SLA along 37 ground tracks at different times in the JES. With a 35-day repeat cycle, all common mode components with periods shorter than the Nyquist period (70 days) will alias into longer period signals unless they are removed from the along-track data. Synoptic SLA maps are a very useful altimeter-derived product. Although some of the aliased signals may be removed by spatiotemporal interpretation of the SLA from all tracks, we illustrate how aliasing effects from neighboring and crossing tracks can combine spatially to mimic mesoscale features in an SLA mapped product.

3. Results

a. De-aliasing satellite altimetry using BP measurements

To demonstrate the significant implications for future and past altimeter data interpretation in marginal seas, we illustrate the aliasing of the common mode in *ERS-2* along-track and gridded products and show how to suppress the alias by subtracting the common mode sampled from the along-track elevation.

Figure 3a shows *ERS-2* along-track elevation during one 35-day orbit cycle in the JES (cycle 51). The intertrack disagreements (called "trackiness errors") are easily seen. For example, there are large SLA disagreements (about 15 cm) between parallel tracks T1 and T2 and at a track cross point marked "C" on the figure. Most interestingly, there is an extensive highland of sea surface topography (circled area) in Fig. 3a. This highland feature is odd because such a giant warm eddy would be rare in the north region of the JES. We suggest in the following that this apparent mesoscale eddy is produced by the combined aliasing effect from neighboring and crossing tracks in this region.

To examine the aliasing source in Fig. 3a, the common mode elevations from BP were subsampled along *ERS-2* tracks for the same 35-day period. The result is shown in Fig. 3b. The sea level elevation along each track is assigned according to the common mode value of SLA at that time. Consequently, Fig. 3b exhibits a large range (about 20 cm) of SLA values when the common mode is subsampled at different along-track times during the 35-day period. Similar to Fig. 3a, large SLA disagreements are evident in Fig. 3b between adjacent tracks T1 and T2 and at track cross point C. This suggests that the trackiness errors in Fig. 3a arise from common mode aliasing. Moreover, aliasing errors from neighboring and crossing tracks produce an extensive highland of SLA in the same region (circled area in Fig. 3b), corresponding to the apparent mesoscale highland of sea surface topography in Fig. 3a. In the next step, we correct the *ERS-2* data for the common mode contribution to SLA by subtracting it from each respective along-track elevation. The common mode observed by BP data (Fig. 3b) was subtracted from Fig. 3a to produce Fig. 3c. The improvement of Fig. 3c is evident: the large SLA disagreement between tracks T2 and T1 is greatly reduced; the same improvement occurs at point C; moreover, the spurious region of sea surface topography disappeared after subtracting the sampled common mode field. It suggests that the highland (circled area) of surface topography in Fig. 3a is actually produced by combined aliasing effect from neighboring and crossing tracks as illustrated by the corresponding circled area in Fig. 3b. On the other hand, it indicates that the BP mean SLA is a good proxy for the common mode in the JES.

Figure 4 is from the AVISO merged SLA product for the period shown in Fig. 3a. It is readily seen that the trackiness errors caused by intertrack disagreements are partially smeared by the interpolation procedure during the mapping. However, the combined aliasing effect from neighboring and crossing tracks remains and produces an artificial mesoscale eddy (circled area in Fig. 4) in the final mapped product. Combined aliasing from a group of ground tracks is a more obstinate aliasing problem than trackiness because of its extensive spatiotemporal influence. The artificial mesoscale eddy is the largest mesoscale feature in Fig. 4, and its impact on the map interpretation is significant.

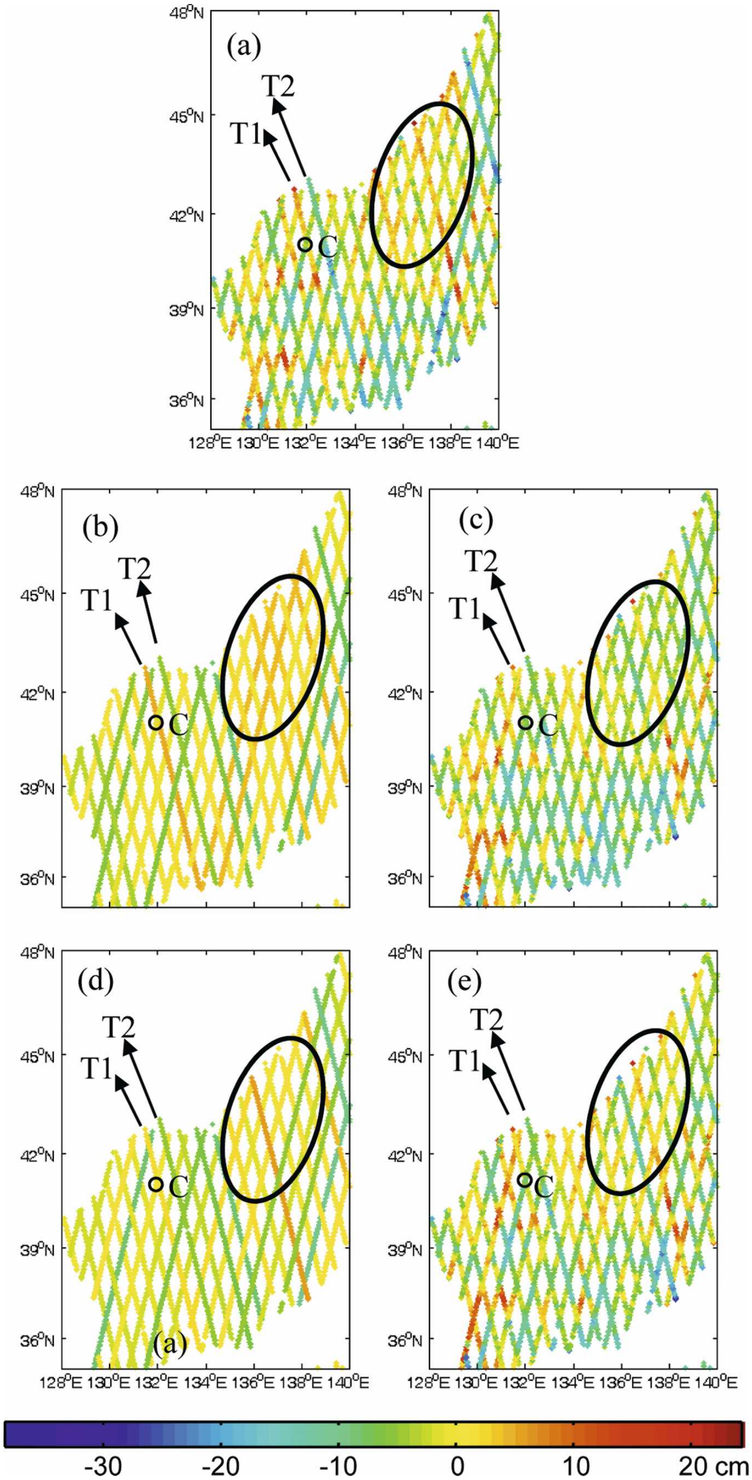

FIG. 3. (a) *ERS-2* along-track elevation for one repeat cycle (cycle 51). (b), (d) Common modes from BP and TG, respectively, sampled along *ERS-2* tracks for the same period. (c), (e) Data from (a) after subtracting (b) and (d), respectively. Tracks T1 and T2, point C, and the highlighted area are discussed in the text. Aliasing is suppressed by removing the common mode, as estimated from BP or TG data.

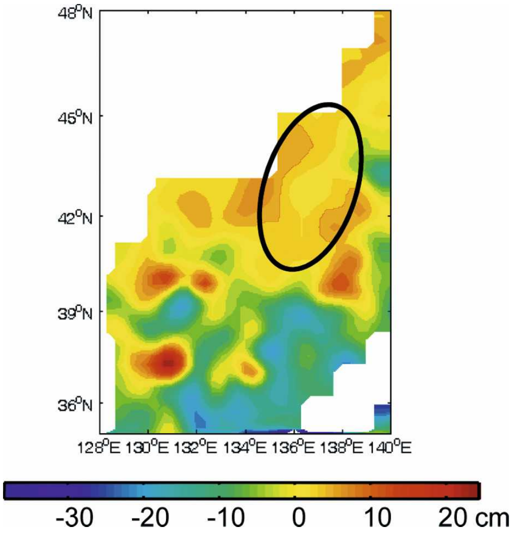

FIG. 4. SLA from the AVISO merged data product for the same period as in Fig. 3a. The circled area corresponds to the circled area indicated in Fig. 3.

b. *A method to suppress the common mode alias in other years*

Our pressure measurements only cover the 2-yr period June 1999–June 2001. It would be valuable to know how to suppress the common mode alias in other years in the JES. We examine the effectiveness of common mode estimates from tide gauges (TGs) because these data are available for long durations.

Hourly TG sea level data from 1999–2001 at sites inside the JES (Fig. 1) were collected from the Japan Oceanographic Data Center and the Korean National Fisheries Research and Development Institute. All the hourly TG data were detided by the same procedure as the BP measurements. To reduce the effects of wind setup and coastal trapped waves on the TG proxy for the common mode, TG records from 17 sites were first individually examined and three stations were excised from the hourly average because they had obviously noisier data (not shown). The averaged and detided BP and TG data have little energy (1%) for periods shorter than 1.2 days. They were subsampled every 12 h at times corresponding with the Navy Operational Global Atmospheric Prediction System (NOGAPS) atmospheric data. We subtracted the local atmospheric pressure from each of the 14 selected TG stations and then averaged them to represent the mean sea level JES. The TG sea level change also includes baroclinic components. We filtered the TG mean sea level with a 70-day high-pass filter in order to remove low-frequency baroclinic variation such as the large-scale seasonal sea level change. The remaining localized baroclinic variability shorter than 70 days would be mostly canceled out by averaging the sea levels at different TGs. Note that the residual baroclinic signals in the estimated common mode could be affected by the number and distribution of the TGs and the relative strength of the baroclinic variability in different marginal seas. Because aliasing error arises from sea level variability at frequencies above the satellite sampling Nyquist frequency, we focus on these higher frequencies. Figure 5 shows the 70-day high-pass filtered common mode signal from BP and from TG, as well as their power spectral density and coherence. The time series and the spectra agree well. Their coherence is high, with little phase difference. The fraction of BP sea level variance captured by the TG time series is calculated by $1 - \sigma_{\mathrm{res}}/\sigma_{\mathrm{tot}}$, where σ_{res} is the variance of the residual of the two time series and σ_{tot} is the total variance of BP sea level anomalies. Using the above equation, the sea level variance from TG data captures about 78% of the sea level variance from the BP. Differences between the TG and BP sea level signals could arise from at least three processes that add to the TG signals: local harbor wind setup, coastal-trapped waves, and baroclinic (steric) signals. The procedure of de-aliasing the common mode signal using TG measurements is illustrated in Figs. 3d and 3e. Figure 3d shows the common mode estimated from TG after subsampling along *ERS-2* tracks during the same 35-day cycle in Fig. 3a. Figure 3e is produced by subtracting Fig. 3d from Fig. 3a. It is readily seen that both the highland of sea surface topography and the trackiness are partially corrected. It indicates that using a common mode estimated from TG can partially (78%) correct the aliasing in satellite altimetric observations in the JES.

4. Summary and discussion

The energetic high-frequency common mode signal in the JES is shown to produce large aliasing errors in satellite altimeter observations. The alias causes large disagreements among neighboring and crossing tracks. Moreover, the along-track sampling of the common mode in a subregion can be relatively higher or lower than that in the surrounding area. This leads to artificial mesoscale features in the synoptic map, qualitatively changing the map interpretation. The common mode signal has an rms amplitude similar to the tide signal in the JES. It suggests the urgent need of common mode correction for the altimetry data in addition to tide correction.

We demonstrate two effective ways to reduce this serious temporal alias. Accurate estimation and best removal of the common mode can be accomplished by one or a few BP gauges in the JES. An alternative

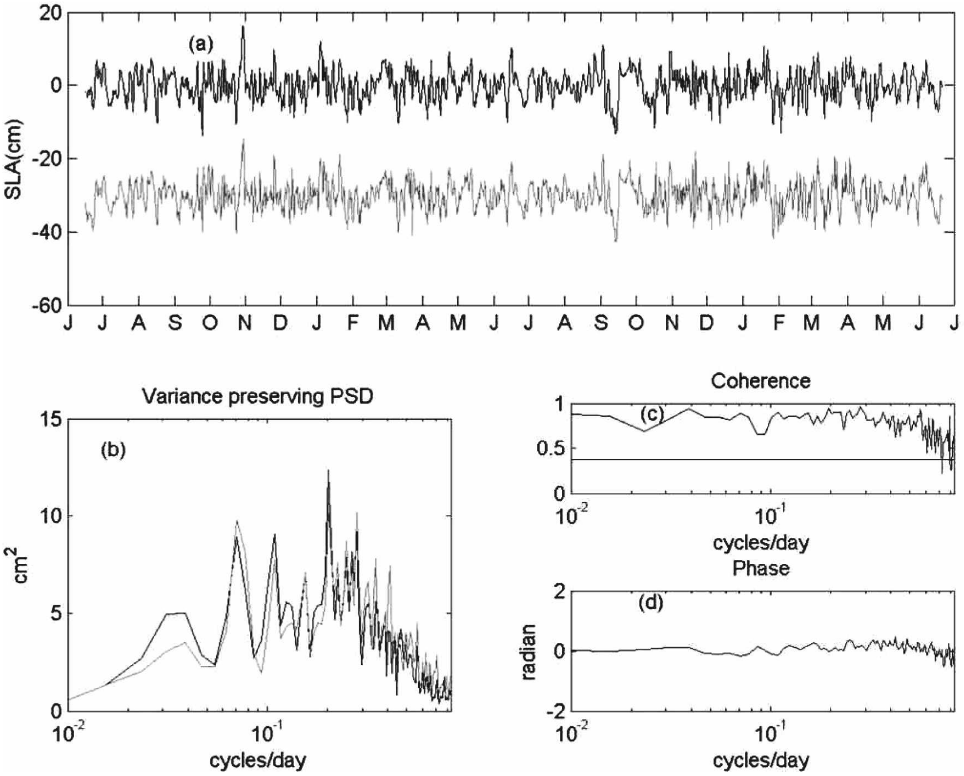

FIG. 5. (a) A 70-day high-pass-filtered common mode from the BP (black) and TG (gray). The gray line has an offset of −30 cm. (b), (c), (d) The variance-preserving spectra, coherence, and phase, respectively. The horizontal thin line in (c) indicates the 95% confidence level.

proxy that accounts for 78% of the common mode variance is afforded by averaging the hourly TG data from 14 coastal sites in the JES (Fig. 1), which are selected for low noise. In the open ocean, Stammer et al. (2000) have suggested using model results to de-alias altimeter signals; Gille and Hughes (2001) confirmed the aliasing of high-frequency variability in altimetry by examining the bottom pressure measurements. Moreover, analysis by Gille et al. (2001) suggested that in the state-of-the-art eddy-resolving models the barotropic response of the ocean to wind forcing may be too fast. We suggest that in situ measurements may be an alternative approach to resolve the problem.

A common mode signal is likely to be found in other nearly enclosed marginal seas (e.g., Garrett 1983; Fukumori et al. 2007). It will produce a substantial alias unless it is removed. We suggest that adding BP measurements would be effective for the future removal of common mode aliasing in satellite observations. Alternatively, BP measurements could also be an ideal data type to assimilate into barotropic models used to infer “high frequency” corrections for the altimeter data. We further suggest that another suitable proxy for removing much of the common mode from past altimeter records may be generated by averaging coastal TG records in marginal seas. If significant high-frequency motions are present in the ocean, both high-quality altimetry and precise gravity missions will require their removal (Tierney et al. 2000). The GRACE mission provides maps of seafloor pressure typically at intervals of 30 days. Bottom pressure signals at periods less than the chosen output interval will alias into those maps and leak nonlocally to other spherical harmonics (S. Jayne 2006, personal communication). However, unlike the altimetry, GRACE measurements at one region are affected by the high-frequency BP variability on a much larger scale. Therefore, high-frequency signal dealiasing of GRACE would also need to consider the BP variability outside the JES. Further discussion of this topic is beyond the scope of this paper.

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