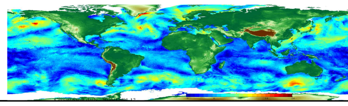

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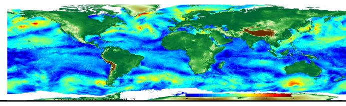

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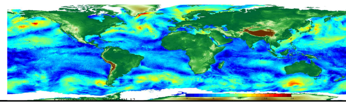


Calculation and Validation of Long Time Series of Satellite Wind Analyses

Abderrahim Bentamy, Fabien Desbiolles, Antoine Grouazel, Bartosz Gorlewicz, Frederic Paul

This report provides an overview of data and method used for the estimation of the global ocean high space and time resolution of sea surface wind analyses. They are calculated based on the use of various remotely sensed wind observations. The wind retrievals (equivalent neutral wind velocities at 10 m) from scatterometer missions since 1992 have been used to build up a 25 years atmospheric climate series. Optimal interpolation and kriging methods have been applied to provide continuously surface wind speed and direction estimates over the global ocean on a regular grid in space and time. The associated parameters such as wind stress amplitude and components, wind vector and stress divergence, and wind vector and stress curls are also provided. The use of ancillary data sources such as radiometer data (SSM/I, SSMIS, WindSat) and atmospheric wind reanalyzes (ERA-Interim) has allowed building a blended product available at 1/4° spatial resolution and every 6 hours from 1992 to 2016. The remotely sensed data are provided by IFREMER (ERS-1 and ERS-2), NASA/JPL (QuikSCAT), EUMETSAT OSI (ASCAT-A, ASCAT-B), from Remote Sensing System (SSM/I SSMIS, and WindSat). The NWP re-analysis is from ECMWF. The accuracy of the resulting wind analyses in determined trough comprehensive comparisons with 6-hourly averaged winds derived from mooring buoy measurements. Buoy and satellite wind estimates compare well with root mean square difference lower than 1.20m/s and 20° for wind speed and direction.

Details related to data, method, and accuracy issues would be found in the following referenced publications (Desbiolles *et al*, 2017), (Bentamy *et al*, 2012, 2013, and 2016)

1 Data and Method

The determination of high space and time wind analysis, called hereafter blended wind, makes of various remotely sensed data mainly from scatterometers onboard the European Remote Sensing Satellite 1 and 2 (ERS-1 and ERS-2), NASA QuikSCAT satellite, and METOP –A and –B (ASCAT-A and –B). Ancillary remotely sensed data are derived from radiometers Special Sensor Microwave Imager and Sounder , SSMI and SSMI/S onboard the Defense Meteorological Satellite Program (DMSP) F10 through F17 satellites, and from WindSat onboard Coriolis satellite.

Scatterometer used in this study are Level 2 wind retrievals available on wind vector cell (WVC) grid within the radar ground swath, i.e., suitable areas (depending on radar characteristics) that allow the determination of wind speed and direction for a number of backscatter coefficients measurements. The WVC grid size varies among different wind products between 12.5 km x 12.5 km (QuikSCAT, ASCAT) and 50 km x 50 km (ERS-1 and -2). Table 1 provides detailed information about each scatterometer, including its operating period, repeat cycle, radar frequency and wavelength. This study employs the swath data (Level2b) of the different missions, as described in Bentamy *et* al. [2016]. In the latter paper, the authors reprocessed ERS-1 and -2 backscatter measurements to ensure consistency between ERS missions, QuikSCAT, and ASCAT observations. QuikSCAT and ASCAT wind retrievals have been corrected to decrease the intermission bias. These adjustments were applied specifically to high-latitude Ku-band retrievals from QuikSCAT (SST-related bias correction) and GMF-related bias correction for C-band ASCAT (*Bentamy et al.* [2011; 2012; 2013] and *Grodsky et al.* [2012]).

The ancillary remotely sensed wind data used in this study are retrieved from SSMI and SSMIS brightness temperature measurements (T_B). Only surface wind speed at 10m height can be derived from SSMIS T_B based on the use of an empirical model fitting the relationship between surface wind speed and T_B through the radiative transfer equation (RTE). They are provided by remote sensing system (RSS) (Wentz, 2013). Full details related to SSMI and SSMIS data as well as to geophysical parameter retrievals may be found in (http://www.remss.com/). SSMIS wind data are available over swath (1400 km width) at wind cell of 0.25° in latitude and longitude over global oceans.

The scatterometer and radiometer wind retrievals are used for estimating 6-hourly (00h:00, 06h:00, 12h:00, 18h:00 UTC) global surface wind analysis with space grid of 0.25° in latitude and longitude. The method is mainly based on the kriging technique with external drift method as described in Bentamy and Croizé-Fillon (2012). Briefly, the objective method assumes that the estimator of "true" wind (unknown) at each grid point for given synoptic times is provided by:

$$\hat{X}_i = \frac{1}{t_b - t_a} \int_{t_a}^{t_b} \left(\sum_{j=1}^{N} \lambda_j \left(X_o^j \left(x_j , y_j , t \right) \right) \right) dt \qquad (1)$$

$\hat{X}_i$ stands for the wind estimator (zonal, meridional or wind speed, each of which considered as a scalar) at grid point $M_i(x_i, y_i)$ over the period $\delta t = t_b - t_a$.

X_o^j Indicates the j-th remotely sensed observation vector available over the satellite swath.

λ_j is the weighting vector to be estimated. Its determination aims at the minimization of the variance difference between and at each grid point (0.25°×0.25°) with the following assumptions:

- unbiased constraint $\sum_{j=1}^{N} \lambda_j = 1$ (2)

- external drift constraint $E(\hat{X}_i) = \alpha_0 + \beta_1 Y_i$ (3)

Where Y_i is the surface wind from European Center of Medium Weather Forecasts (ECMWF) available at the epoch of $M_i(x_i, y_i)$.

Based on mathematical development (details may be found in Bentamy and Croizé-Fillon, 2002), weight λ_j , and constraint constants α_0 , and β_1 are solutions of a linear system including the spatial and temporal wind structure functions.

2 Resulting wind field analyses

Figure 1 shows examples of surface wind analyses associated with the tropical cyclone Mathiew event occurring over Caribbean sea on 29 September 2016 through 9 October 2016. It illustrates the spatial and temporal variability of wind vector through four successive analysis epochs (00h:00, 06h:00, 12h:00, and 18h:00 UTC). To further assess the spatial and temporal variabilities, blended winds are compared to buoy data. Figure 2 shows time series of 6-hourly averaged estimated from NDBC buoys named WMO 42058 and 42052 and located at 14.98°N-74.99°W, and 15.25°-67.51°W, respectively. Times series derived from blended analyses and occurring close to buoy locations are also shown. Blended wind speed tracks well buoy data. For instance, the spatial and temporal changes of wind speed maxima are well depicted from blended analyses and compare well to those obtained from moorings.

Table1 : Summary of scatterometer's mission characteristics and L2 wind product characteristics

Scatterometer	Period	Cycle	Frequency	Agency
ERS-1	Aug 1991 – Mar 1992	3 days	C-band (5.3GHz, 5.7 cm)	ESA
	Apr 1992 – Dec 1993	35 days		
	Dec 1993 – Apr 1994	3 days		
	Apr 1994 – Mar 1995	168 days		
	Mar 1995 – May 1996	35 days		
ERS-2	Apr 1995 – Jan 2001	35 days	C-band (5.3GHz, 5.7 cm)	ESA
QuikSCAT	Jul 1999 – Nov 2009	4 days	Ku-band (13.4GHz, 2.2 cm)	JPL
ASCAT	Oct 2006 – Present	29 days	C-band (5.3GHz, 5.7 cm)	EUMETSAT

The accuracy of blended wind fields is mainly determined trough comprehensive with buoy data available from various networks such as National Data Buoy Center (NDBC) and Tropical Atmosphere Ocean (TAO), Prediction and the Research Moored Array in the Atlantic (PIRATA), and the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA) . NDBC buoys are moored off the US coasts, spanning the latitudes from 20°N to 65°N (www.ndbc.noaa.gov). TAO, PIRATA, and RAMA buoys are moored in the tropical Pacific, Atlantic, and Indian, respectively and are referred to as tropical buoys (www.pmel.noaa.gov/tao/). To provide compatibility with blended winds, the buoy measurements are transformed into ENW at standard 10-m height using the COARE3.0 algorithm of Fairall *et al* (2003). For comparison with blended winds, all valid buoy data available within 3 hours from the epoch analysis times (00h:00, 06h:00, 12h:00, 18h:00 UTC) are arithmetically averaged. The results are referred to as 6-hourly buoy wind estimates. For comparison purpose, buoys and blended 6-hourly data are collocated in space (<25km) and time.

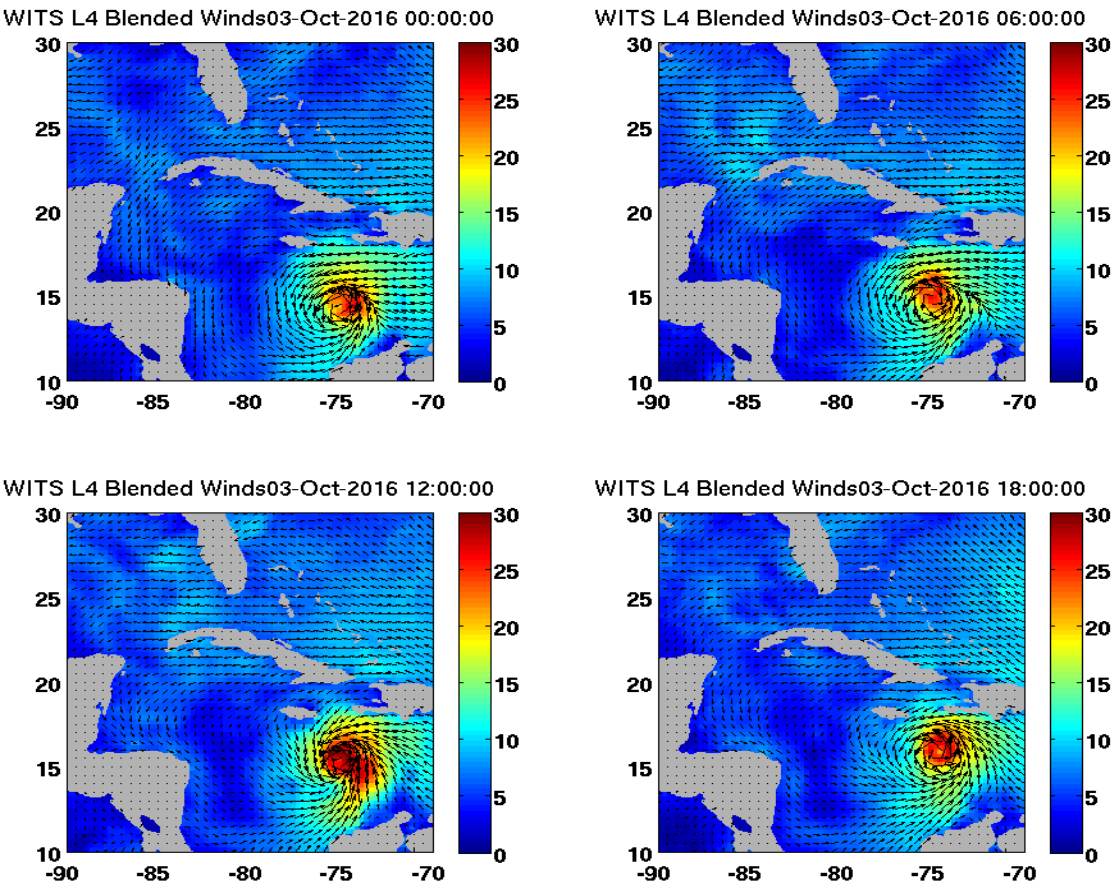


Figure1 : The four epoch surface wind speed (in color and in m/s) and direction (black arrows) analyses occurring on 3 October 2016 and associated with Tropical cyclone Mathiew

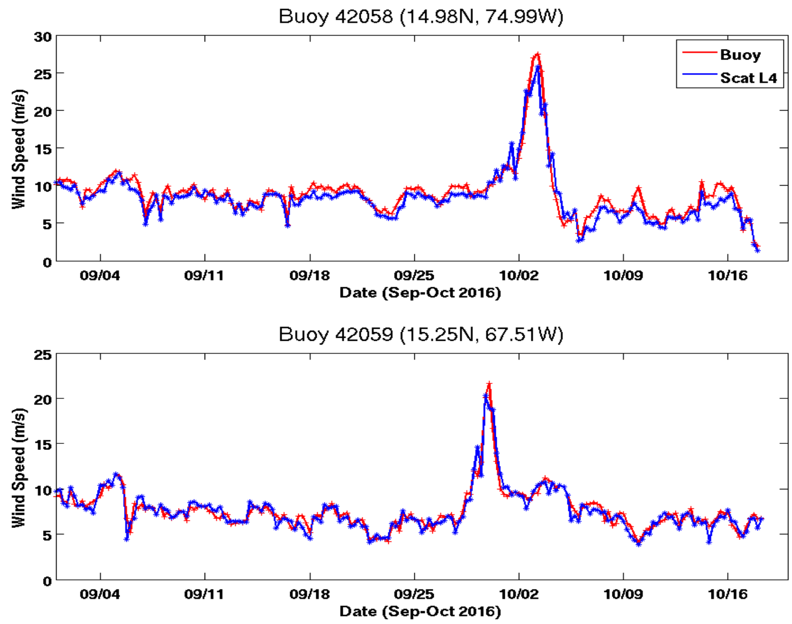


Figure2 : Time series of buoy (red line) and blended (blue) occurring during TC Mathiew event.

3 Accuracy of wind field analyses

The accuracy of blended wind fields is mainly determined trough comprehensive with buoy data available from various networks such as National Data Buoy Center (NDBC) and Tropical Atmosphere Ocean (TAO), Prediction and the Research Moored Array in the Atlantic (PIRATA), and the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA) . NDBC buoys are moored off the US coasts, spanning the latitudes from 20°N to 65°N (www.ndbc.noaa.gov). TAO, PIRATA, and RAMA buoys are moored in the tropical Pacific, Atlantic, and Indian, respectively and are referred to as tropical buoys (www.pmel.noaa.gov/tao/). To provide compatibility with blended winds, the buoy measurements are transformed into ENW at standard 10-m height using the COARE3.0 algorithm of *Fairall et al (*2003). For comparison with blended winds, all valid buoy data available within 3 hours from the epoch analysis times (00h:00, 06h:00, 12h:00, 18h:00 UTC) are arithmetically averaged. The results are referred to as 6-hourly buoy wind estimates. For comparison purpose, buoys and blended 6-hourly data are collocated in space (<25km) and time

Only results drawn from NDBC buoy and satellite 6-hourly wind comparisons are shown in this report. The numbers of observations of collocated data for the whole period (1992 – 2016) is 2119912. Figure 3 illustrates example of 6-hourly wind speed comparisons. It shows results associated with blended winds and with ERA Interim re-analyses. The accuracy of the blended wind analyses is characterized by the first statistical moments of their differences with collocated buoy data (Table 2). The statistics are estimated for the moorings located offshore (>50 km off the shoreline) and at nearshore sites. For the offshore comparison, the overall mean difference (bias) between buoy and satellite wind speeds is quite small, and the associated standard deviation (STD) is about 1.20 m/s. Although the bias on wind direction is small, it indicates that directions of the blended winds are slightly rotated anticlockwise compared to buoy data. The STD of the wind direction difference is lower than 20°, showing the good agreement between the wind directions of different sources. The fair agreement between NDBC and blended wind speeds as well as wind directions are also confirmed by scalar correlation (ρ), symmetrical linear regression coefficient (bs) for only the wind speed, and by vector correlation (ρ^2) for wind direction. The statistics related to NDBC nearshore comparison are quite poorer. Nevertheless, the nearshore blended winds show a good agreement with buoy data in terms of root mean square (RMS) difference, lower than 2 m/s, and correlation and symmetrical coefficients exceed 0.86.

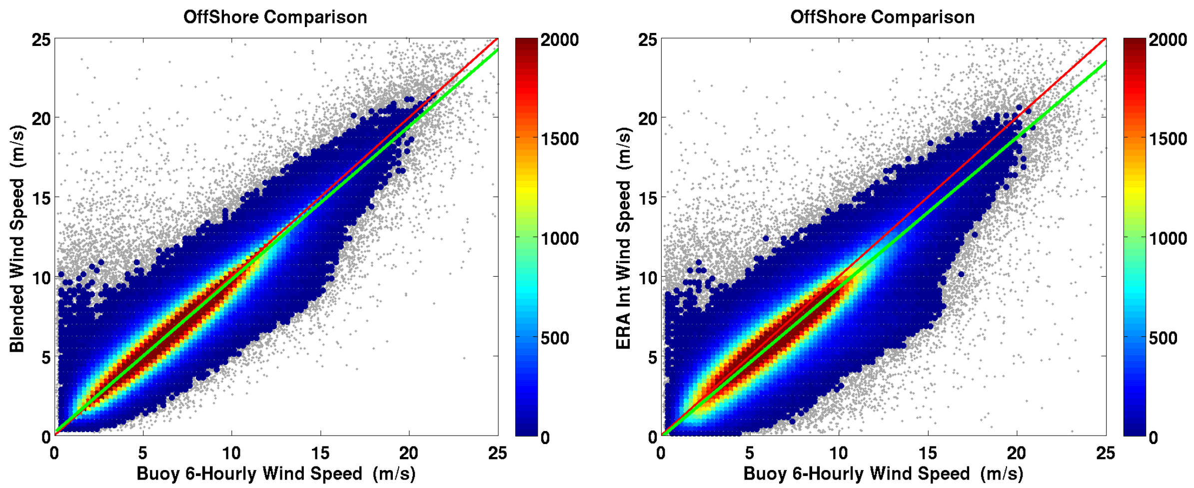


Figure 3: Comparisons of 6-hourly 10m wind speeds from buoy and blended (left panel) and ERA Interim (right panel), determined from collocated data occurring during the whole study period 1992 – 2016. Red and green lines indicate perfect (1^{st} bissectrice) and linear regression lines, respectively.

Table 2: Statistical comparison results of collocated 6-hourly buoy and blended 10m wind speed and direction. They are only estimated for the period (March 1992 – December 2016). Bias is defined as the mean difference between buoy and blended winds (in this order). STD, bs, ρ, ρ^2 , and indicate the standard deviation, regression symmetrical coefficient, scalar correlation coefficient, and vector correlation coefficient, respectively. The latter varies between -2 and +2.

		Wind Speed				Wind Direction		
Moorings	Length	Bias (m/s)	STD (m/s)	bs	ρ	Bias (deg)	STD (deg)	ρ^2
NDBC offshore	1135110	0.08	1.25	0.95	0.93	-4	18	1.83
NDBC nearshore	984802	0.43	1.79	0.86	0.87	-7	26	1.52

Additional accuracy tests are performed as a function of time. Figure 4 shows the time series of monthly mean and STD difference between offshore NDBC and blended 6-hourly wind estimates, the associated correlation coefficient, and the sampling length of data used for monthly calculations. The results are shown for the whole study period (March 1992 – December 2016). Wind speed bias values (Fig. 4a) do not exceed 0.30 m/s, and more than 90% of the values are less than 0.20 m/s. Similar results are found for the zonal and meridional biases. The STD differences (Fig. 4b) for the wind speed and for the associated components are lower than 1.20 m/s and 2 m/s, respectively. Wind speed difference STD are quite consistent during the study period, while STD differences related to the zonal and meridional components tend to be slightly higher during the period 1992–2000 compared to 2000–2016. This is partly due to the change in sampling length (Fig. 4d), and especially due to the use of QuikSCAT and ASCAT wind directions for the blended calculations. Time series of scalar correlation coefficients assess the good agreement between buoy and blended winds during the whole period. The three correlation coefficients (Fig. 4c) exceed 0.95. The lowest values are about 0.92.

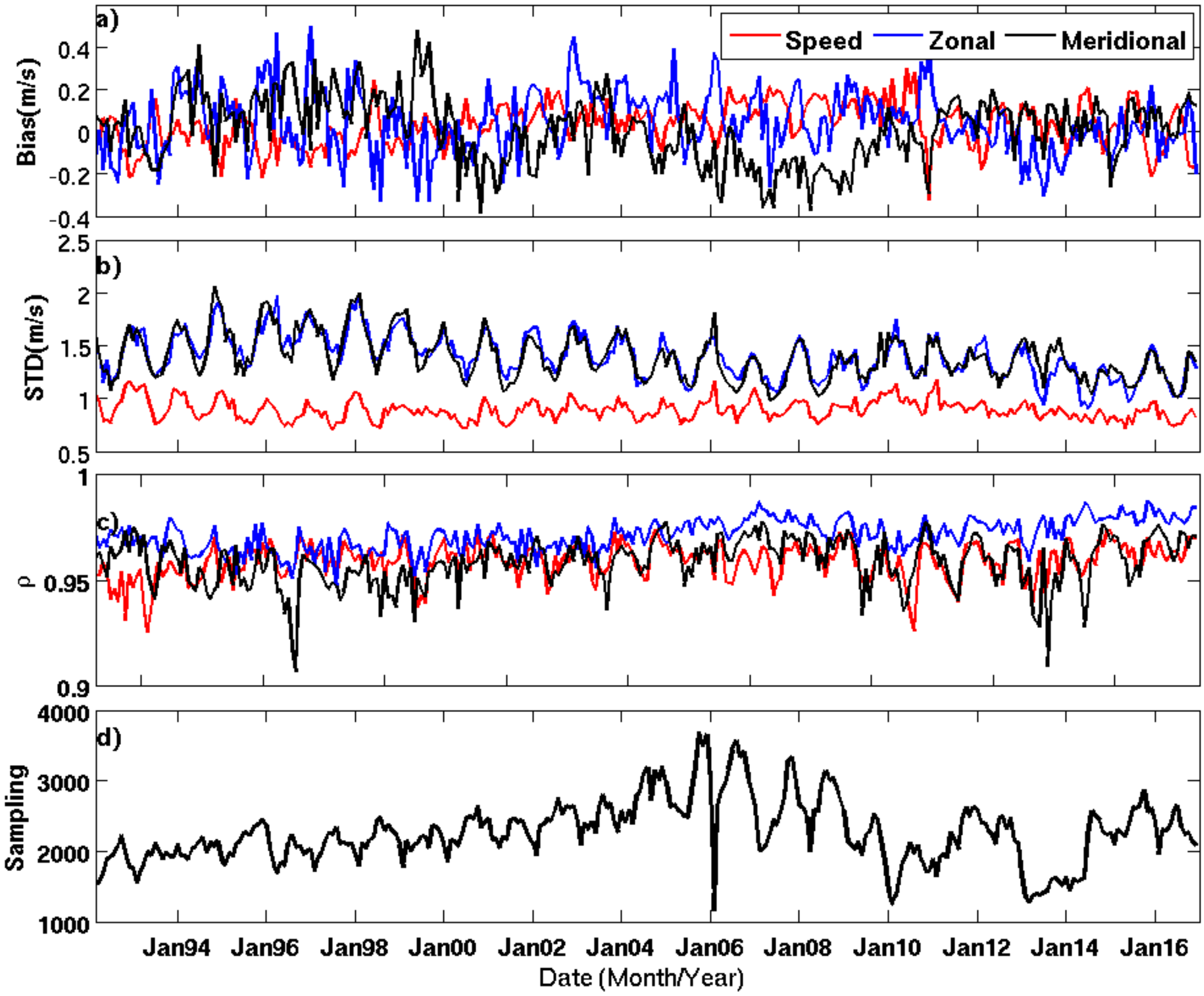
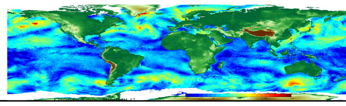


Figure 4 : Time series of the statistical parameters characterizing the comparison between offshore NDBC and blended 6-hourly wind speed (red), zonal (blue), and meridional (black) components: a) mean difference (Bias), b) Standard deviation (STD) difference, c) scalar correlation coefficient (ρ), and d) sampling length



Acknowledgments

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