HF Radar Processing Using “Nearest-Neighbor” Statistics

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by:

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Abstract:

Temporal and "nearest neighbor" spatial statistics have been developed for the quality control of high frequency radar (HF Radar) measurements at Bodega Marine Laboratory. The techniques are particularly attractive for systems with greatly fluctuating range, where standard techniques either: (1) limit the footprint over which measurements are extracted, or (2) have the potential for presenting a biased picture of the flow field at the limits of the system coverage. The statistics presented herein use a blend of temporal derivatives and spatial comparisons to quantify the acceptability of a given current measurement. Distances to the nearest valid measurements, angular differences between a given current measurement and currents measured nearby, and magnitude differences are all used to flag currents as either acceptable or unacceptable. The techniques have been validated on both long-range (200 kilometer nominal range, 5 kilometer resolution) and standard-range (60 kilometer nominal range, 2 kilometer resolution) systems. The methods have been encoded in Matlab scripts that are compatible with the publicly available HFR_Progs toolbox.

1. Introduction:

Quality control of HF Radar measurements is a central processing issue for data dissemination, especially with the advent of national data distribution networks and the proliferation of user-defined methods. A few of the widely used quality control methods are: (1) optimal interpolation, an objective mapping technique [Kim, et. al., 2007], (2) open-boundary modal analysis [Kaplan and Lekien, 2007], (3) empirical orthogonal function (EOF) fitting, whereby currents are reconstructed from the dominant EOFs [e.g., Kaplan, et. al., 2006], and (4) temporal averaging. The first three techniques have potential limitations when the system footprint experiences large fluctuations. Either measurements recorded outside of the borders of the normal system coverage must be discarded, or hard-to-verify statistical assumptions about "filling in" data in areas of sparse coverage must be made. EOF analysis in particular suffers from coverage limitations. The last method (averaging) degrades the temporal resolution of the measurements.

The temporal and spatial nearest neighbor techniques described herein were developed at Bodega Marine Laboratory in response to large fluctuations in the long-range HF Radar (CODAR) system footprint (Figure 1). The two long-range systems (200 km nominal range) combine to yield surface currents over a coverage area that typically fluctuates between 2,500 and 10,000 km^2. The fluctuation is presumably driven by the combined influences of the effects of wave height on signal return and the geometrical layout of the systems (Halle and Largier, 2008, submitted to *J. Atmos. Oceanic Technol.*). The techniques have been extended to the standard range system processing as well, with modification of selected screening levels due to the increased spatial resolution. The methods have been encoded as Matlab scripts for ease of use and compatibility with the publicly available HFR_Progs toolbox (Kaplan and Cook, 2007, available for download at http://www.cencalcurrents.org/docsANDsoft.shtml). The resulting currents have been mapped using the M_Map Matlab toolbox (Pawlowicz, 2007, available for download at http://www.eos.ubc.ca/~rich/).

One approach to quality control of radials and totals associated with large range fluctuations is to simply use (or increase the severity of) “standard” despiking. For example, one can modify the acceptable level of geometric dilution of precision (GDOP). Such harshness often has the disadvantage of discarding large numbers of seemingly valid measurements. The statistical levels presented herein for the BML systems reflect an attempt to balance the need for quality control with a desire to extract the greatest possible number of useful measurements from the systems.

The methods described herein are not “stand alone”. In other words, their use does not preclude the use of other methods. They can be used in sequence, such that screened radials or totals can in turn be passed to other methods (such as optimal interpolation or open-boundary modal analysis) for further processing.

The entire procedure of obtaining total current vectors from radial measurements is not discussed here. Other standard techniques (radial masking, current speed limitations, etc.) are also part of the process for converting radial velocity measurements into total current vectors.

Although the sequence of quality control steps documented in this paper has not been optimized for efficiency, the speed of statistical calculation and screening is not particularly onerous. However, it is entirely possible that fewer steps employing different parameters would yield similar results. Various sequences can be investigated using the HFR_Progs-compatible routines developed for this project.

The rest of this paper is divided into 4 main sections: Method Overview, Radial Vector Cleaning, Total Vector Quality Control, and Summary. Appendices, Acknowledgements, and References follow.

2. Method Overview

This section outlines the quality control process. The basic flow for converting radial current measurements into vector estimates of surface currents is:

1. Basic radial “good data” checks.
2. Radial temporal statistics calculation and quality control.
3. Calculation/gridding of initial set of totals.
4. Initial cleaning of totals using standard parameters (GDOP, etc.)
5. Cleaning of totals using nearest neighbor spatial and temporal statistics.

The process is summarized in Figure 2.

The radial “good data” checks are standard. They include such things as checks to ensure that the timestamps of the collected data are correct, that the data is unique (e.g., not simply a copy of data collected during the previous measurement period), etc. These are detailed further in Appendix A.

The temporal and spatial “cleaning” steps (Steps 2 and 5) are composed of varying numbers of screening loops, with different quality control parameters for each loop.

The temporal statistics are based on specifying a window that is shorter than the typical timescale of system coverage fluctuations. The sliding window is used to calculate percent coverage statistics at each gridded location. Forward and backward (in time) derivatives of current velocity are also calculated. Currents that change too rapidly are suspect.

The total list of derived statistics is presented in Table 1. Not all of these statistics need be (or are) used at every site, but the complete list of statistics coded into the routines is presented. The limits used for screening radial and total vectors at BML are detailed in succeeding sections of the paper.

The “nearest neighbor” spatial statistics are based on both proximity and current differences. In other words, distances from a given current measurement to the nearest 3 (or 5, or 10) gridded locations with valid current measurements are calculated and used as a basis for screening. Differences in both current speed and direction between the gridded measurement of interest and its neighbors are also used as “goodness measures”.

The list of spatial statistics is presented in Table 2. These are used at BML for processing total vectors (not radials). Again, not all statistics are employed for every set of total vectors, but are presented here for completeness.

The levels for flagging suspect data may not be the same for all sites and systems. Interactive routines have been written to aid in determining acceptable levels. The routines generally allow the user to decide which statistic, screening level, and time to investigate, and automatically generate snapshots of the unscreened and screened data. The real strength of the interactive routines is they are set up to automatically determine which statistics have been calculated by reading the fields from the statistics structure, enabling new user-generated statistics to be easily screened.

3. Radial Vector Cleaning

Radial current measurements are passed through the temporal statistics screening twice (Figure 4). The statistics used, as well as their values, may presumably be site specific. The quality control parameters used for the BML radars are listed in Table 3.

Prior to calculating statistics, the radials are “lightly gridded” by assuming that measurements within 0.01 kilometers in range, 0.49 degrees in bearing/heading to/from the radar, and separated by less than 0.5 kilometers represent the same location. This simply ensures that any slight changes in recording or operations do not affect the resulting statistics. It is not the same as the grid used to generate the set of total vectors, although the totals grid could presumably be used as well.

4. Total Vector Quality Control

The “cleaned” radials are combined into total surface current vectors and mapped onto a uniform grid using standard techniques. An initial screening for surface currents of suspect quality is performed using GDOP. These preliminary surface currents will be referred to as “geometrically screened” in this section.

Quality control of the “geometrically screened “ total vectors is performed using multiple passes (Figure 5). The temporal (spatial) statistics used for both the standard and long range systems are summarized in Table 4 (Table 5).

A useful feature of the spatial statistics is that the screening levels (for example, the parameter SumDist5) can be adjusted to account for spatial gaps. Occasionally, for example, valid current measurements are made fairly close to the inshore edge of coverage and at mid-range, with a gap between. If there are only a few current estimates at mid-range (beyond the gap), they are likely to be unrealistic. If several measurements are clustered together at mid-range, examination (not shown) reveals that they are more likely to appear valid.

An example of the quality control applied to the currents measured by the long-range system is provided in Figure 6. The first panel shows the geometrically screened totals, and the second panel shows the currents after application of the temporal and spatial quality control methods presented herein. Simply screening using a larger value of GDOP would help to remove some of the erroneous current measurements at the edge of the domain, but often results in the removal of some seemingly valid measurements as well. In addition, screening with GDOP also does not always remove “spikes” in the current measurements. The statistics presented herein potentially allow for removal of obviously bad data without resorting to more extreme application of standard measures.

5. Summary

Both temporal and “nearest neighbor” statistics have been developed to allow for quality control of HF Radar data without the restrictions imposed by other methods. The parameters may be site dependent. Those that have been found useful for the standard- and long-range systems at Bodega Marine Laboratory are presented in Tables 3, 4, and 5.

As previously mentioned, Matlab routines to calculate the statistics and to interactively investigate the effects of setting quality control levels on the currents have been developed. These may be incorporated into future releases of HFR_Progs. In the meantime, they are available for download at http://www.bml.ucdavis.edu/boon/.

One advantage of these statistics appears to be the relaxation of the upper bound restriction on valid radial current measurements. For example, the strongest currents offshore Bodega are typically 100 cm/s. The maximum “allowable speed” for a valid radial current measurement can be set to 150 cm/s (or even 200 cm/s) when followed by the use of the statistics detailed herein. High current speeds are only filtered out of the measurements if they appear to be unrealistic. This has proven to be useful at BML, where some surprisingly high (for California) current speeds have been recorded during extended wind events.

It often appears adequate to follow the temporal and spatial quality control by linear and spatial interpolation (Figure 6b). For example, long-range system total currents have subsequently been linearly spatially interpolated across the domain, filling in the small gaps each hour by the bounding currents. Linear temporal interpolation across time gaps of up to four hours has also been also employed. However, it is possible to follow this screening with more sophisticated interpolation schemes such as optimal interpolation or open-boundary modal analysis.

Acknowledgements

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Appendix A

Initial Radial Data Check

The initial data screening checks are listed here for completeness (Table A1). The checks serve to ensure that the files contain measurements, that the measurement timestamp corresponds to the time that the file was saved, etc. Checks are also performed to make sure that each data file is “unique”, or not simply a copy of a previous data file.

Notes below Table A1 provide more detail for selected parameters.

References

Kaplan, D.M., and J. Largier (2006), HF radar-derived origin and destination of surface waters off Bodega Bay, California, *Deep-Sea Res. Part II*, doi: 10.1016/j.dsr2.2006.07.012.

Kaplan, D.M., and F. Lekien (2007), Spatial interpolation and filtering of surface current data based on open-boundary modal analysis, *J. Geophys. Res.,* 112, C12007, doi:10.1029/2006JC003984.

Kim, S.Y., E. Terril, and B. Cornuelle (2007), Objectively mapping HF radar-derived surface current data using measured and idealized data covariance matrices, *J. Geophys. Res.,* 112, C06021, doi:10.1029/2006JC003756.

National Data Buoy Center (2007), http://www.ndbc.noaa.gov.

Table 1. Temporal Statistics

Temporal Statistic	Description
DuDtFwd[a]	The first derivative of the east velocity calculated using the next valid measurement.
DvDtFwd[a]	The first derivative of the north velocity calculated using the next valid measurement.
DuDtBwd[a]	The first derivative of the east velocity calculated using the previous valid measurement.
DvDtBwd[a]	The first derivative of the north velocity calculated using the previous valid measurement.
TotDiffFwd[a]	The magnitude of the first derivative, calculated from DuDtFwd and DvDtFwd.
TotDiffBwd[a]	The magnitude of the first derivative, calculated from DuDtBwd and DvDtBwd.
MaxTotDiff[a]	The maximum of TotDiffFwd and TotDiffBwd.
MinTotDiff[a]	The minimum of TotDiffFwd and TotDiffBwd.
PerCovMin[b,c]	The minimum percentage of time that coverage exists at a given gridded location, calculated using a series of sliding windows of constant duration.
PerCovMax[b,c]	The maximum percentage of time that coverage exists at a given gridded location, calculated using a series of sliding windows of constant duration.
PerCovTyp[b,c]	The "typical" (mode) percentage of time that coverage exists at a given gridded location, calculated using a series of sliding windows of constant duration.
PerCovMedian[b,c]	The median percentage of time that coverage exists at a given gridded location, calculated using a series of sliding windows of constant duration.

Notes: [a] The maximum window length for calculating the derivatives is user-specified. The closest valid current measurement within the window is used to calculate the derivatives. If no valid measurements are found, the associated derivative is set to not-a-number (NaN). [b] The window length for calculating percent coverage statistics is also user-specified. At each location (and for each individual timestep), a percent coverage time series is calculated by stepping this constant duration window past the measurement of concern one step at a time. The coverage statistics are calculated from this series. The process is then repeated for the next location, then the next time for which measurements are available, etc. [c] Figure 3 presents a schematic of the percent coverage calculation using a sliding window.

Table 2. Spatial Statistics

SumDist3	Sum of the distances to the nearest 3 gridded locations with valid measurements.
SumDist5	Sum of the distances to the nearest 5 gridded locations with valid measurements..
SumDist10	Sum of the distances to the nearest 10 gridded locations with valid measurements.
AvDist3	Average of the distances to the nearest 3 gridded locations with valid measurements.
AvDist5	Average of the distances to the nearest 5 gridded locations with valid measurements.
AvDist10	Average of the distances to the nearest 10 gridded locations with valid measurements.
SumAngle1p5[a]	Sum of the absolute value of the angle differences between the measurement of concern and all valid measurements up to 1.5 times the grid spacing away. . If the velocity magnitudes of the measurement under consideration and a nearby measurement are both under 20 cm/s, the absolute angular difference for that individual comparison is set to zero. All of the comparisons are then summed to obtain the statistic.
SumAngle2p0[a]	Sum of the absolute value of the angle differences between the measurement of concern and all valid measurements up to 2.0 times the grid spacing away. . If the velocity magnitudes of the measurement under consideration and a nearby measurement are both under 35 cm/s, the absolute angular difference for that individual comparison is set to zero. All of the comparisons are then summed to obtain the statistic.
SumAngle5p0[a]	Sum of the absolute value of the angle differences between the measurement of concern and all valid measurements up to 5.0 times the grid spacing away. If the velocity magnitudes of the measurement under consideration and a nearby measurement are both under 50 cm/s, the absolute angular difference for that individual comparison is set to zero. All of the comparisons are then summed to obtain the statistic.
AvAngle1p5[a]	Average of the angle differences between the measurement of concern and all valid measurements up to 1.5 times the grid spacing away (calculated from SumAngle1p5).
AvAngle2p0[a]	Average of the angle differences between the measurement of concern and all valid measurements up to 2.0 times the grid spacing away (calculated from

	SumAngle2p0).
AvAngle5p0[a]	Average of the angle differences between the measurement of concern and all valid measurements up to 5.0 times the grid spacing away (calculated from SumAngle5p0).
AvMagRatio1p5	The current speed at a given gridded location divided by the average current speed obtained from all valid measurements up to 1.5 times the grid spacing away.
AvMagRatio2p0	The current speed at a given gridded location divided by the average current speed obtained from all valid measurements up to 2.0 times the grid spacing away.
AvMagRatio5p0	The current speed at a given gridded location divided by the average current speed obtained from all valid measurements up to 5.0 times the grid spacing away.

Notes: [a] The speed thresholds used for the angular difference calculation ensure that only “large” currents contribute to measurement of angular difference. Mismatches in the directions of large magnitude currents are simply the differences that catch the eye when looking at maps of current data, although one could possibly argue for a physical basis for such speed thresholds.

Table 3a. Radial Temporal Statistics - Standard Range Systems [a]

Statistic Name	Value	Currents To Flag
MinTotDiff [b,c]	0.003 cm/s^2	Above Limit
PerCovMax [d]	35 %	Below Limit

Notes: [a] The standard range systems provide hourly current estimates at 2 kilometer resolution. [b] The window used for MinTotDiff (and all derivative) calculation is 4 hours. Only valid measurements within a four-hour window from the measurement under consideration are used to calculate the derivative. [c] A velocity derivative of 0.003 cm/s^2 roughly corresponds to a change of 11 cm/s in one hour. [d] The sliding window used to calculate PerCovMax (and all percent coverage statistics) is 8 hours in duration, centered on the measurement in question (so 9 hourly measurements are used). If the maximum percent coverage at a given location using this sliding window is below 35%, the associated measurement is set to not-a-number (NaN).

Table 3b. Radial Temporal Statistics - Long Range Systems [a]

Statistic Name	Value	Currents To Flag
MinTotDiff [b,c]	0.0019 cm/s^2	Above Limit
PerCovMax [b]	35 %	Below Limit

Notes: [a] The long range systems provide hourly current estimates at 5 kilometer resolution. [b] The windows used statistic calculation are the same as for the standard range systems (Table 3a). [c] A velocity derivative of 0.0019 cm/s^2 roughly corresponds to a change of 7 cm/s in one hour.

Table 4. Total Vector Temporal Statistics - Standard- and Long Range Systems

Statistic Name	Value	Currents To Flag
Limits Set 1 [a]		
MinTotDiff	0.003 cm/s^2	Above Limit
PerCovTyp [b]	35 %	Below Limit
Limits Set 2 [c]		
MinTotDiff [b]	0.003 cm/s^2	Above Limit

Notes: [a] The windows for Limits Set 1 are 4 hours (for MinTotDiff) and 8 hours (for PerCovTyp). Only valid measurements within a four-hour window from the measurement under consideration are used to calculate the derivative. A sliding window that includes hourly measurements within eight hours is used to calculate the percent coverage statistic. [b] A velocity derivative of 0.003 cm/s^2 roughly corresponds to a change of 11 cm/s in one hour. [c] The window for Limits Set 2 is 3 hours for MinTotDiff. Only valid measurements within a three-hour window from the measurement under consideration are used to calculate the derivative.

Table 5a. Total Vector Spatial Statistics - Standard Range Systems[a]

Statistic Name	Value	Currents To Flag
Limits Set 1		
SumDist3	8 km	Above Limit
SumDist5	18 km	Above Limit
Limits Set 2		
SumDist3	8 km	Above Limit
SumDist5	18 km	Above Limit
SumDist10	40 km	Above Limit
AvAngle1p5	60 degrees	Above Limit
SumAngle1p5	300 degrees	Above Limit
AvMagRatio1p5	0.1 - 2	Outside of Limits

Notes: [a] The standard range systems provide hourly current estimates with 2 kilometer resolution.

Table 5b. Total Vector Spatial Statistics - Long Range Systems[a]

Statistic Name	Value	Currents To Flag
Limits Set 1		
SumDist3	20 km	Above Limit
SumDist5	45 km	Above Limit
Limits Set 2		
SumDist3	20 km	Above Limit
SumDist5	45 km	Above Limit
SumDist10	100 km	Above Limit
AvAngle1p5	60 degrees	Above Limit
SumAngle1p5	300 degrees	Above Limit
AvMagRatio1p5	0.1 - 2	Outside of Limits

Notes: [a] The long range systems provide hourly current estimates with 5 kilometer resolution.

Table A1. Initial Radial Data Checks[a]

Statistic or Information	Statistic Description
FileNames	File name containing a selected (hourly) set of radials for a given site.
SiteNames	Name of the site as read from the file.
FileTimes	Time that the data was saved, recorded by the processing system and noted In the file.
FileTimeStamp	Time stamp on the saved file, recorded by the archival system.
FileFound	A simple switch, equal to one (1) if the desired file has been saved.
DataFound	A simple switch, equal to one (1) if radials have been recorded in the file.
NotWobblyFiles [b]	A check on radial quality.
MatchingTimeStamps	A simple switch, equal to one (1) if the FileTime matches the FileTimeStamp.
GriddedCurrentsUnique [c]	A check to ensure that the radials recorded at a specified time are unique. Refer to notes for more information.
NonNaNGriddedCurrentsUnique [d]	A check to ensure that the radials recorded at a specified time are unique. Refer to notes for more information
PerDiffFwd [e]	The percentage of radial measurements at a specified time that are different from the closest succeeding valid set of radial measurements.
PerDiffBwd [f]	The percentage of radial measurements at a specified time that are different from the closest preceeding valid set of radial measurements.
NumRadsInMask	The number of radial measurements at a specified time inside the user-defined radial mask.
NumRadsOutsideMask	The number of radial measurements at a specified time outside the user-defined radial mask.
NumRadsTotal	The number of total radial measurements returned at a specified time.
MaxRange	The maximum range of radial measurements returned at a specified time.
MinRange	The minimum range of radial measurements returned at a specified time.
MinBear	The minimum bearing of radial measurements returned at a specified time.

MaxBear	The maximum bearing of radial measurements returned at a specified time.

Notes: [a] Checks developed at BML in italics, otherwise the checks are those provided by David Kaplan and Mike Cook. [b] NotWobblyFiles: A site-specific switch used to check one of the early systems for consistent range and bearing spacing of returned radials. Provided by Mike Cook and David Kaplan. [c] *GriddedCurrentsUnique*: A switch used to determine if the radial currents at a particular time are unique (e.g., is the system frozen?). This statistic includes all holes in the data, so that locations with invalid (or no) measurements returned at both times are considered equal. This statistic is likely to yield invalid results when the range is low, in the sense that it may indicate the radials are the same when they are not. The radials are considered unique when *PerDiffFwd* and *PerDiffBwd*, calculated with the gaps in the data, are greater than 70%. [d] *NonNanGriddedCurrentsUnique*: A switch used to determine if the radial currents at a particular time are unique (e.g., is the system frozen?). This statistic does not include holes (spatial gaps) in the measurements. The radials are considered unique when *PerDiffFwd* and *PerDiffBwd* are greater than 70%. [e] *PerDiffFwd*: The percentage of radial currents at a specified time that are different from those obtained at the next succeeding time for which measurements exist. The percentage can be calculated based on all data (including spatial gaps) for *GriddedCurrentsUnique*, or based only on locations where valid measurements have been returned for *NonNaNGriddedCurrentsUnique*. The latter is saved as *PerDiffFwd* for the statistics used at BML. Locations with measurements whose magnitudes differ by less than 0.1 cm/s for both times being compared are considered equal (not different). [f] *PerDiffBwd*: The percentage of radial currents at a specified time that are different from those obtained at the closest preceeding time for which measurements exist. The percentage can be calculated based on all data (including spatial gaps) for *GriddedCurrentsUnique*, or based only on locations where valid measurements have been returned for *NonNaNGriddedCurrentsUnique*. The latter is saved as *PerDiffBwd* for the statistics used at BML. Locations with measurements whose magnitudes differ by less than 0.1 cm/s for both times being compared are considered equal (not different).

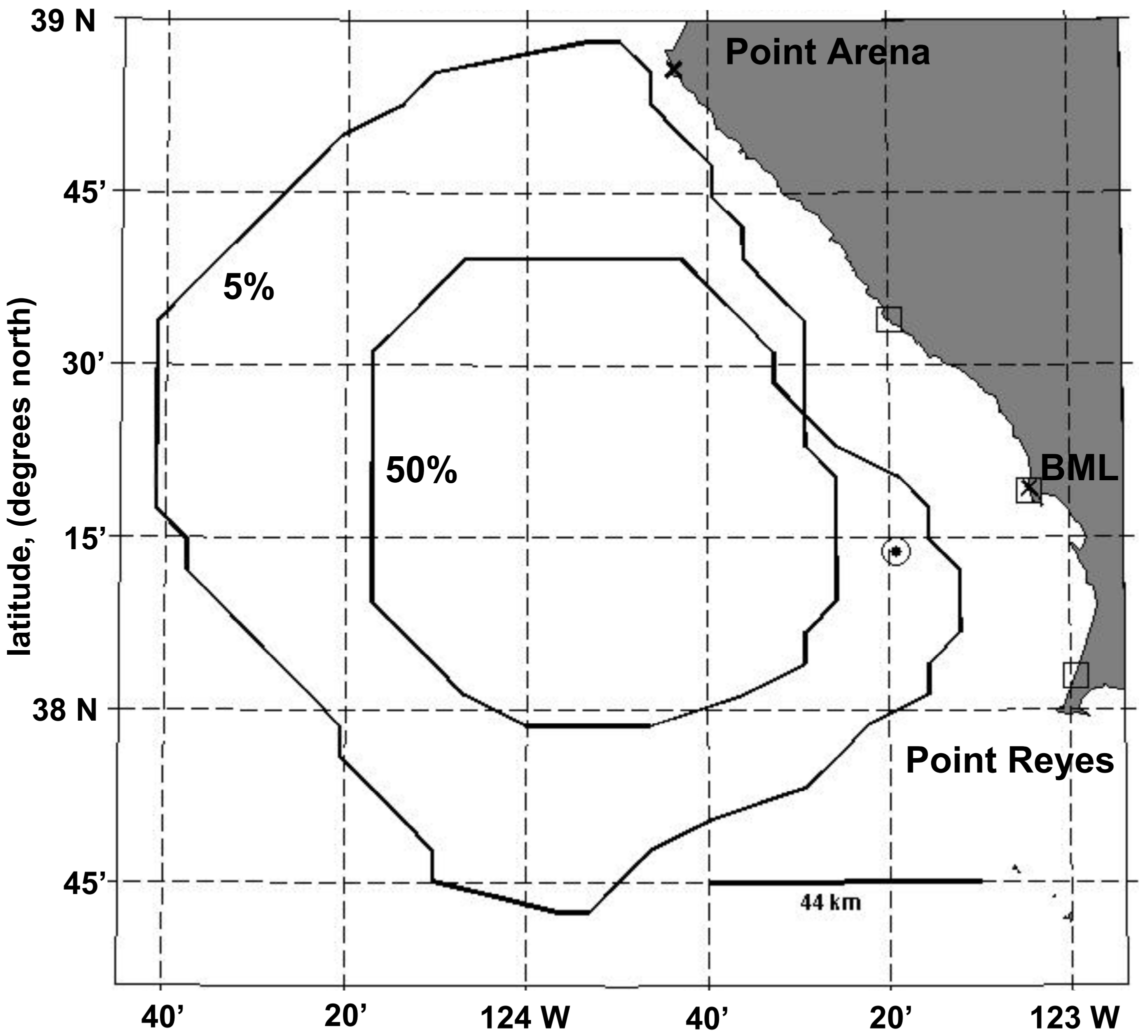


Figure 1. Percent coverage map of the long-range system total vector surface currents offshore Bodega Marine Lab (BML). The 50% (5%) contour level indicates that hourly surface currents are obtained inside the indicated region over 50% (5%) of the time during the period June-August 2007. BML currently operates two long-range systems (X's) and two standard-range systems (squares). NDBC buoy 46013 is located at the bullseye [National Data Buoy Center, 2007]. The standard range coverage is not shown.

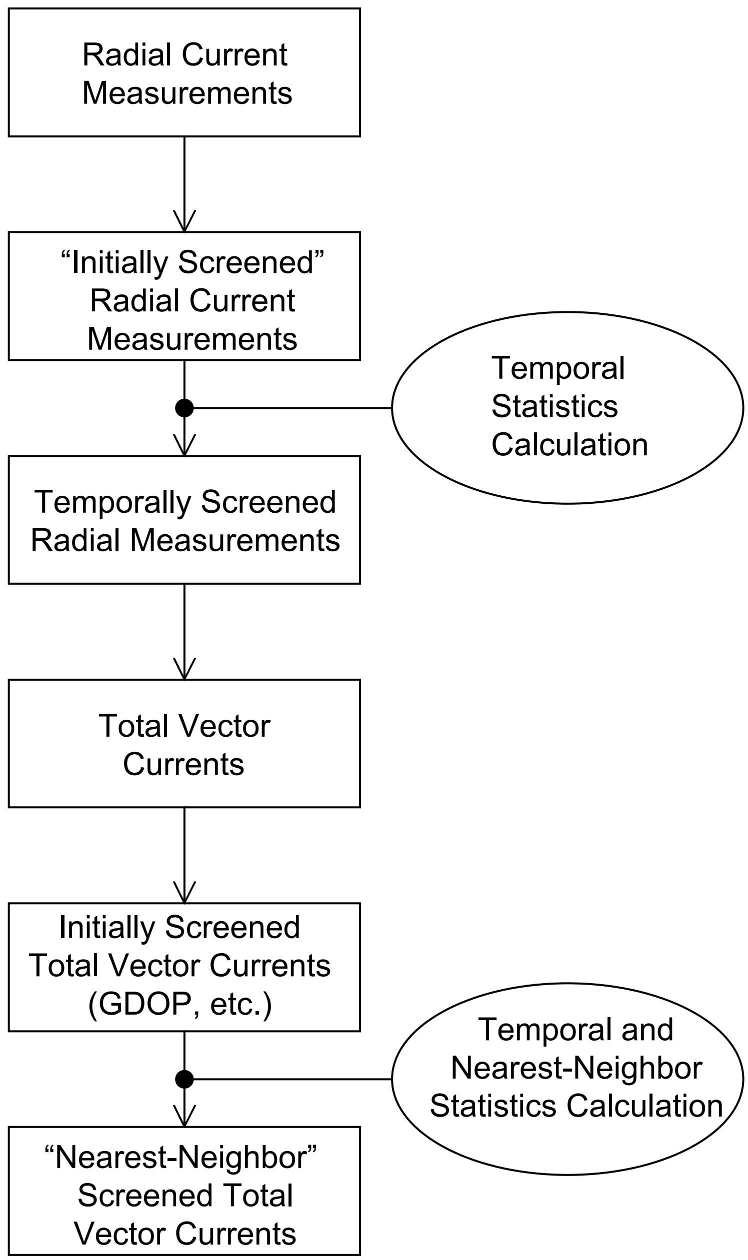
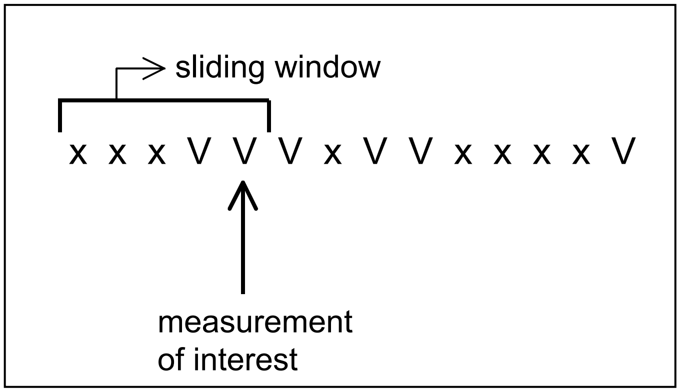


Figure 2. Total current vector calculation flowchart. The temporal and spatial statistics described in this paper are used in the sequence as shown by the circles in the right column.



<u>Figure 3.</u> Schematic of percent coverage calculation. The illustrative "time series" is defined such that x is an "invalid" measurement or NaN, and V is a "valid" measurement. Assuming hourly averages, five hours (including the measurement of interest) are examined in this scenario. The percentage coverage estimates using the sliding window are 40, 60, 60, 80, and 80 percent. The percent coverage statistics in this case (refer to Table 1 for definitions) are: PerCovMin of 40%, PerCovTyp (mode) of either 60 or 80%, PerCovMedian of 60%, and PerCovMax of 80%. Nine hourly measurements are typically used to derive percent coverage statistics at BML.

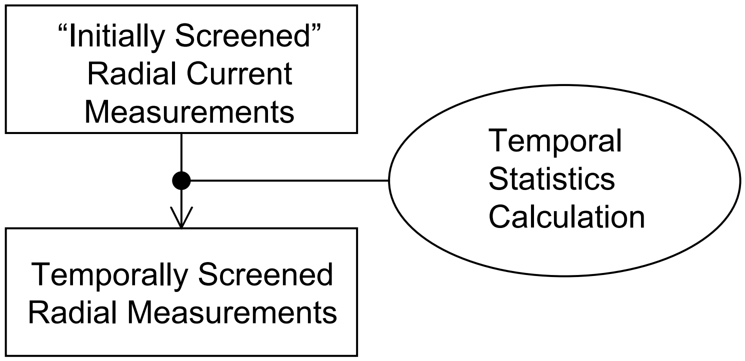


Figure 4. Temporal radial screening flowchart. A single-pass method is used. This is not due to optimization, but reflects the need to remove only the most physically unrealizable radials, because of the fine cleaning of the total current vectors. Screening levels are listed in Tables 3a (standard-range systems) and 3b (long-range systems).

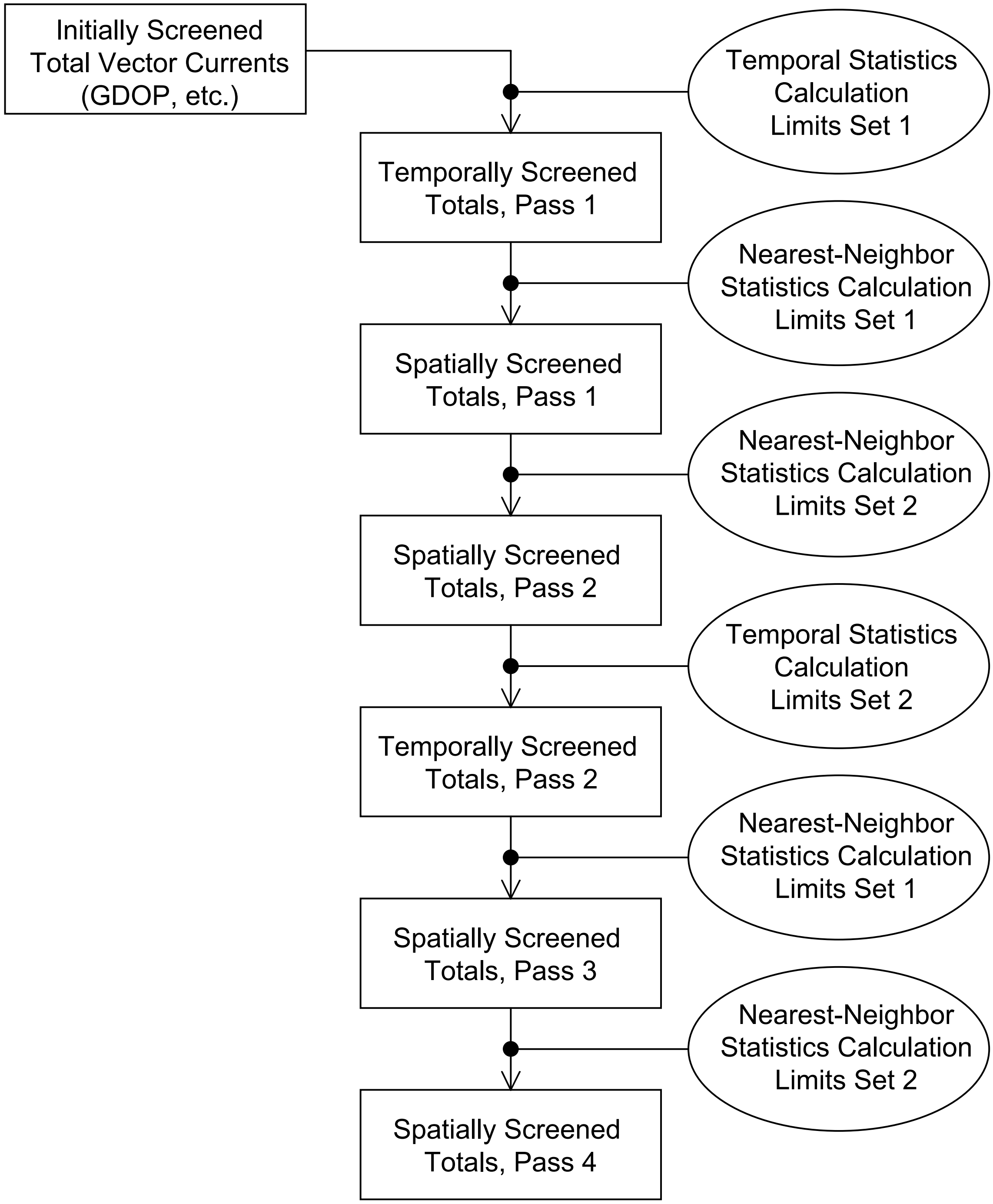


Figure 5. Total current vector quality control flowchart. This is a multi-pass process, with two sets of spatial screening levels and two sets of temporal screening levels. The process has not been fully optimized, so it is possible that other combinations of screening levels and/or numbers of processing steps could lead to similar results. The temporal screening levels are listed in Tables 4a (standard-range systems) and 4b (long-range systems). Tables 5a and 5b list the nearest neighbor spatial screening levels.

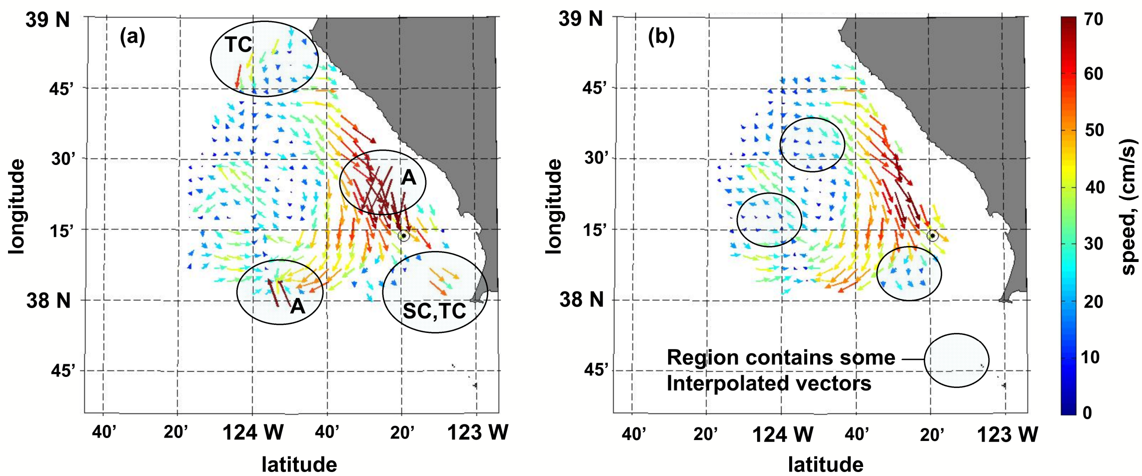


Figure 6. Hourly surface currents measured by the long-range system, June 27, 2007 1600 GMT. Panel (a) shows the currents after screening using standard GDOP-type parameters. Panel (b) shows the currents after the additional spatial and temporal screening discussed in this paper. The shaded circles in panel (a) indicate areas of currents removed after the additional screening. The circles marked "A" emphasize currents typically removed to violation of the angular screening criteria. The circle marked "SC, TC" indicates the removal of currents due to sparse spatial and temporal coverage. "TC" indicates currents removed to sparse temporal coverage. Note that temporal screening (derivatives) were also used. Untangling the combined effects of spatial and temporal screening at any one time is difficult. The indicated regions are suggestive of the process rather than statistical measures of all of the screening criteria used for this particular set of currents. The circles in panel (b) indicate regions that contain at least one interpolated current.