Two Improvements in Omega Windfinding Techniques

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ABSTRACT

A one-dimensional local spline smoothing technique is applied to Omega navigational signals for the purpose of windfinding. Wind profiles so produced depend largely on two parameters of the smoothing procedure: the nodal spacing, which determines the smallest resolvable scale, and a filtering wavelength, which produces the necessary smoothing of the phase data, and prevents representational distortion of any power from the unresolved scales. Phase "noise" from stationary test sondes is superimposed on synthetic Omega signals to compare wind profiles obtained with this new procedure with profiles computed using other techniques.

Is it shown that the effect of aircraft maneuvers on Omega wind accuracy is not completely removed by the normal practice of evaluating all phase derivatives at a common time. Additional improvements in accuracy of 2–3 m s^{-1} can be obtained by a "rate-aiding" technique using aircraft navigational data.

1. Introduction

In 1982, the Hurricane Research Division of the Atlantic Oceanographic and Meteorological Laboratory (HRD) began to develop and implement computer software for the postprocessing of data from Omega dropwindsondes (ODWs). In addition to data obtained during HRD's Synoptic-Flow Experiment (Burpee et al., 1984), ODW data from other major field experiments have been postprocessed at HRD, including the 1982 Alpine Experiment (ALPEX), and most recently, the Genesis of Atlantic Lows Experiment (GALE). Since 1982, HRD has examined and compared various windfinding algorithms in an effort to improve wind measurement accuracy from ODWs. We have concentrated on two aspects of Omega windfinding from aircraft-launched ODWs: first, the general problem of smoothing noisy Omega phase data, and second, the influence of aircraft maneuvers on wind accuracy. Some results of these investigations have been reported by Franklin and Julian (1985).

Franklin and Julian examined the accuracy and character of Omega wind profiles using three common phase-smoothing algorithms. They concluded that of the three procedures (quadratic least-squares fit, low-pass filter, and cubic spline), Passi's cubic spline smoothing (1977) showed the least sensitivity to phase noise; on this basis, the spline algorithm was recommended for use in ODW postprocessing. A new smoothing algorithm, similar to the Passi spline, has been implemented at HRD; we will report herein on a comparison of this new method with existing techniques.

Aircraft turns affect ODW wind estimates because Omega transmitters broadcast in sequence, and because the measurement of phase is made on the aircraft, not the ODW. During turns, phase measurements from different stations are contaminated by varying components of aircraft motion. The windfinding equations (Franklin and Julian) can only eliminate aircraft components that are constant over the 10-s phase transmission sequence. Early attempts to correct this problem used aircraft ground speed and heading information to normalize the measured phases, a method known as "rate-aiding" (Cole et al., 1973). Gradually, this became less popular as phase-smoothing algorithms became more sophisticated. Phase data for each station were smoothed independently using analytic functions (quadratic least-squares fits, for example). Phase rates were then obtained by evaluating the derivatives of these functions for each station at *a common* time, rather than at its particular time of transmission (Julian, 1982). Despite this correction, in their study of the effect of turns on ODW wind estimates, Franklin and Julian found that turns were associated with real-time (not postprocessed) wind measurement errors 50% larger than during straight and level flight (legs). Much of this difference was due to phase noise that could be removed in postprocessing; however, even after postprocessing, wind errors in turns were about 25% higher than in legs. We therefore took a second look at rate-aiding, the results of which appear here.

2. Least-squares fitting with a derivative constraint

A new phase-smoothing algorithm, least-squares fitting with a derivative constraint, has been implemented at the Hurricane Research Division of the Atlantic Oceanographic and Meteorological Laboratory. This

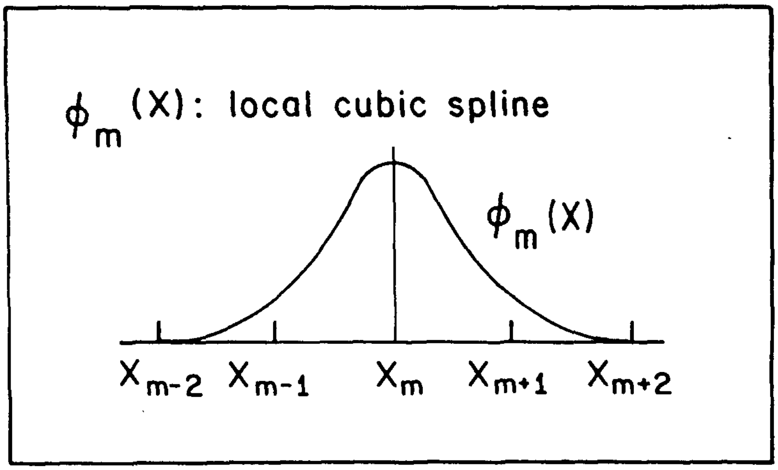

FIG. 1. The local cubic spline function $\phi_m(x)$; $\phi_m(x)$ is identically zero beyond $2\Delta x$ from x_m.

algorithm, developed by K. V. Ooyama, is described as follows.

Consider a continuous domain $[x_0, x_M]$ spanned by $M + 1$ equally spaced nodes at locations $x_m = x_0 + m\Delta x$, $m = 0, 1, \cdots M$, where $\Delta x = (x_M - x_0)/M$. At each node, a local basis function

$$\phi_m(x) \equiv \Phi[(x - x_m)/\Delta x] \tag{1}$$

is assigned (Fig. 1), where Φ is the cubic B-spline, defined for the nondimensional coordinate ξ as

$$\Phi(\xi) = \begin{cases} 0 & \text{if } \quad |\xi| \geq 2, \\ 0.25\,(2 - |\xi|)^3 & \text{if } \quad 2 > |\xi| \geq 1, \\ 0.25\,(2 - |\xi|)^3 - (1 - |\xi|)^3 & \text{if } \quad 1 > |\xi| \geq 0. \end{cases} \tag{2}$$

For ease of notation, we define two additional nodes outside the domain, at $x_{-1} = x_0 - \Delta x$ and at $x_{M+1} = x_M + \Delta x$. The choice of local cubic splines as basis functions is discussed by Ooyama (1984).

Given a set of J phase observations $\hat{u}(\hat{x}_j)$ from the domain $[x_0, x_M]$ at locations $\hat{x}_j$, $j = 1, 2, \cdots, J$, the smoothing algorithm determines the continuous function $u(x)$, given by

$$u(x) = \sum_{m=-1}^{M+1} a_m \phi_m(x), \tag{3}$$

which satisfies the least-squares condition

$$\sum_{j=1}^{J} [u(\hat{x}_j) - \hat{u}(\hat{x}_j)]^2 \Delta x + \int_{x_0}^{x_M} \alpha [D^{(k)}(u)]^2 dx = \text{minimum}. \tag{4}$$

In (4), $D^{(k)}$ denotes the kth derivative with respect to x. The second term in (4) acts as a filter; it is the "derivative constraint". The parameter α is defined by

$$\alpha = (L_c \Delta x / 2\pi)^{2k} \tag{5}$$

where $L_c\Delta x$ is the filter half-power wavelength. In applying this procedure to the smoothing of Omega phase data, we set k equal to 3, Δx equal to 40 s, and $L_c = 9$ (half-power wavelength = 360 s).

An attractive feature of this algorithm is the availability of several types of boundary conditions. At present we set the second derivative of phase to be zero at the top and bottom end points of the sounding (x_0 and x_M). This condition on phase results in constant wind (zero shear) at the end points. Although the zero shear condition is the best choice available, it might or might not suit a particular sounding. Consequently, computed winds near the end points of all soundings are routinely discarded.

Once the boundary conditions at x_0 and x_M are chosen, (3) can be written in the closed form

$$u(x) = \sum_{m=0}^{M} a_m \psi_m(x) \tag{6}$$

where

$$\psi_m(x) = \begin{cases} \phi_m(x) + \beta_m \phi_{-1}(x), & m = 0, 1, \\ \phi_m(x) + \beta_m \phi_{M+1}(x), & m = M, M-1, \\ \phi_m(x), & m = 2, 3, \cdots M-2. \end{cases} \tag{7}$$

Our choice of the foregoing boundary conditions determines the β_m: $\beta_0 = 2$, $\beta_M = 2$, $\beta_1 = -1$, $\beta_{M-1} = -1$.

Substitution of (6) into (4) yields a system of M equations for a_m that can be solved using standard techniques:

$$\sum_{m'=0}^{M} (p_{mm'} + \alpha q_{mm'}) a_{m'} = b_m \quad \text{for } m = 0, 1, \cdots M, \tag{8}$$

where

$$b_m = \sum_{j=1}^{J} \psi_m(\hat{x}_j)\hat{u}(\hat{x}_j)\Delta x,$$

$$p_{mm'} = \sum_{j=1}^{J} \psi_m(\hat{x}_j)\psi_{m'}(\hat{x}_j)\Delta x,$$

$$q_{mm'} = \int_{x_0}^{x_M} D^{(k)}(\psi_m)D^{(k)}(\psi_{m'})dx. \quad (9)$$

The cubic spline algorithm of Passi (1974, 1977), which has been the postprocessing windfinding algorithm at HRD, is similar to the local spline algorithm just described. The Passi algorithm divides the entire sequence of phase observations into segments of 180 s, and fits cubic polynomials to each segment by least squares, subject to continuity restrictions at the join points. Although the Ooyama ("local") and Passi ("segmented") spline algorithms are described in rather different terms, they are mathematically equivalent, with the exception of the derivative constraint and boundary condition flexibility of Ooyama's procedure.

The advantage of the local spline algorithm lies in the filtering properties of its derivative constraint, which allow a more accurate depiction of the wind sounding. This is due to representational distortion of spectral power in wavelengths near $2\Delta x$: for example, a $2\Delta x$ cosine wave with maxima and minima at alternating nodes is approximately representable, while the $2\Delta x$ sine wave, with maxima and minima between the nodes, has no representation. Waves smaller than $2\Delta x$ ("noise") are not represented. With no filtering mechanism other than the nodal spacing, the segmented spline must have Δx large in order to eliminate noise from the smoothed phases. Passi sets Δx to be 180 s; representational distortion then occurs near the 360 s wavelength. With typical ODW fall rates of 25–30 mb min^{-1}, this is approximately a 150–175 mb vertical scale. The amount of distortion in the computed winds will depend upon how much power is present in these scales for any particular sounding. With the local spline smoother, we have set Δx to 40 s. Any representational distortion now occurs in vertical wavelengths of about 35 mb, an unresolvable scale in which noise and signal are inextricably intertwined. With L_c equal to 9, these distorted waves are removed, along with all others shorter than 360 s (150–175 mb), in accordance with the derivative constraint response function.

Utility of the new procedure for Omega windfinding was evaluated using the test ODW data from Franklin and Julian (1985). Phases from the leg segments of their 1982 flight were extracted and pieced together to form a phase "sounding" reflecting only linear aircraft motion and measurement noise (the ODW was stationary on a Key Largo, Florida beach). A second, independent sounding was constructed from a similar experiment in 1985. The results of this noise sensitivity test are shown in Table 1. *The smoothing parameters used in the low-pass filter and segmented spline profiles are those recommended by their authors,* Julian (1982) and Passi (1974), respectively. The table confirms that the segmented spline is the strongest smoother of noise. The local spline also smooths fairly well, followed by the low-pass filter and quadratic fit. Errors for the 1982 sounding are higher than for the 1985 sounding due to the lack of a good signal from the Hawaii transmitter on the day of the 1982 experiment, and because of generally higher noise levels for all stations on that day.

TABLE 1. Sounding-mean wind errors (m s^{-1}) for "noise only" soundings.

Smoother	1982 flight	1985 flight
Segmented spline	1.73	0.45
Local spline	2.00	0.77
Filter	2.16	1.03
Quadratic	2.70	1.27

Phase smoothing reduces the resolution of wind shear in an Omega wind profile; during the 3- or 4-min smoothing interval, an ODW will fall 75–100 mb. Franklin and Julian created a synthetic sounding of noise-free phases using data from a rawinsonde ascent through a cold front, and computed the sounding-mean wind error for this "shear-only" sounding for the quadratic, filter, and segmented spline smoothers. Table 2 reviews those results, to which we add our calculation for the local spline smoother. The order of finish is, not surprisingly, the inverse of that in Table 1, although the segmented spline's resolution is decidedly poorer than that of the other three algorithms, all of which have mean errors of about 1 m s^{-1}.

None of the soundings from Tables 1 or 2 are, by themselves, realistic tests for the phase-smoothers. Franklin and Julian devised a crude noise model to superimpose on the "shear-only" sounding; however, a more realistic procedure can be used. The "noise-only" phases from Table 1 can be superimposed on the synthetic sounding of Table 2 to produce phase profiles typical of what might be measured in real life. Mean wind errors for these two "natural" soundings are given in Table 3.

Examination of computed wind profiles (not shown) and the mean wind errors given in Table 3 suggest that the low-pass filter and local cubic spline smoothers offer the best balance between smoothing noise and resolving the small-scale wind features. This is largely a matter of "tuning"; errors with the segmented spline are high because it cannot resolve the smaller features in the wind field (its nodal separation is 180 s). Errors with the quadratic are high because it responds to very small-scale noise in the Omega data (Franklin and Julian, 1985). Phase noise during the 1982 and 1985 experiments was normal, or perhaps a little worse than normal, based on our ODW experience in the western

TABLE 2. Sounding-mean wind errors for "shear only" sounding.

Smoother	Mean wind error ($m\ s^{-1}$)
Quadratic	0.90
Filter	1.03
Local spline	1.08
Segmented spline	1.87

Atlantic and eastern Pacific regions. We think, therefore, that a smoothing algorithm which performed well in these tests should perform well in general.

Naturally, the segmented spline could be "tuned in" to these data by reducing the length of the individual cubic segments; however, representational distortion of the shorter wavelengths would remain. The local spline procedure can take advantage of short nodal spacing and avoid this distortion due to its built-in filter. It is primarily for this reason that we would prefer a local spline wind profile over a similarly "tuned" segmented spline profile.

Wind profiles computed with the low-pass filter (with parameters specified by Julian) are largely similar to those computed with the local cubic spline. There is one minor reason to prefer the spline, however. While none of the windfinders can provide accurate wind estimates close to the top and bottom end points of a sounding, the boundary conditions available with the spline seem to confine this deterioration to within 45 mb of the endpoints. Although this problem has not been investigated for the low-pass filter, wind accuracy would probably begin to deteriorate about 60 mb from the top and bottom endpoints.

3. Phase normalization by aircraft motion

The phase-smoothing algorithms in use at HRD correct for the effects of aircraft accelerations by evaluating phase rates for the different Omega stations at a common time, rather than at the time each station broadcasts. Despite this traditional correction (Julian, 1982), wind errors in the vicinity of turns were found to be significantly higher than those during straight and level flight (Franklin and Julian, 1985). Intuition suggests a possible sampling problem: to prevent errors from occurring during a turn, the phase smoother must identically reproduce the aircraft component of phase-rate for each Omega sequence smoothed. Phase-rates change rapidly in a turn, relative to the frequency with which the turn is sampled. Furthermore, each Omega station samples the turn at a different set of stages. To the extent that the aircraft component in each station's phases is not identically reproduced, the technique of evaluating phase-rates at a common time will not eliminate wind error. There are alternative procedures, however. Another technique for removing the aircraft component of retransmitted phase is known as "rate-aiding" (Cole et al., 1973), in which aircraft ground speed and track information is used to "normalize" the phase *before* the phase-smoothing is performed. The normalized phases do not have sharp kinks for the smoothers to negotiate. We have implemented such a rate-aiding procedure for use during ODW postprocessing at HRD; it is used in addition to the "time shifting" approach already found in the smoothers.

Table 4 shows mean wind errors for the turn portions of a stationary test ODW, in an experiment similar to the one described by Franklin and Julian. Winds were computed using quadratic smoothing. In this test, rate-aiding was slightly more effective at removing the effects of the turn than the time shifting approach. This sounding, unfortunately, is the only stationary test for which aircraft track and speed information is available for rate-aiding. We must therefore turn to our large sample of hurricane soundings (where the "true" wind is unknown) for additional (subjective) evidence. Figure 2 shows the u and v wind components for an ODW dropped northwest of Hurricane Debby in 1982. The aircraft executed a turn as the ODW neared the surface. For each phase smoother, winds computed using the (standard) time shifting correction are shown along with a second wind sounding in which the aircraft motion was first removed by rate-aiding. Vector differences are seen to reach several meters per second at times. Although "truth" is not known, the reduced variability in the rate-aided winds suggests that the change represents an improvement. A survey of turns during HRD's Debby and Josephine (1984) ODW experiments (Burpee et al., 1984) computed with and without rate-aiding, shows that rate-aiding frequently reduces suspicious excursions of the computed winds, with vector differences typically 1–2 $m\ s^{-1}$.

Figure 2c illustrates that rate-aiding can have a sig-

TABLE 3. Sounding-mean wind errors ($m\ s^{-1}$) for "natural" soundings.

Smoother	1982 noise and shear	1985 noise and shear
Filter	2.22	1.64
Local spline	2.28	1.65
Segmented spline	2.74	2.00
Quadratic	2.81	1.84

TABLE 4. Mean wind error (turns) for stationary test ODW, for various turn removal techniques.

Technique	Mean wind error ($m\ s^{-1}$)
None	3.20
Time shifting	1.96
Rate-aiding	1.87
Both	1.87

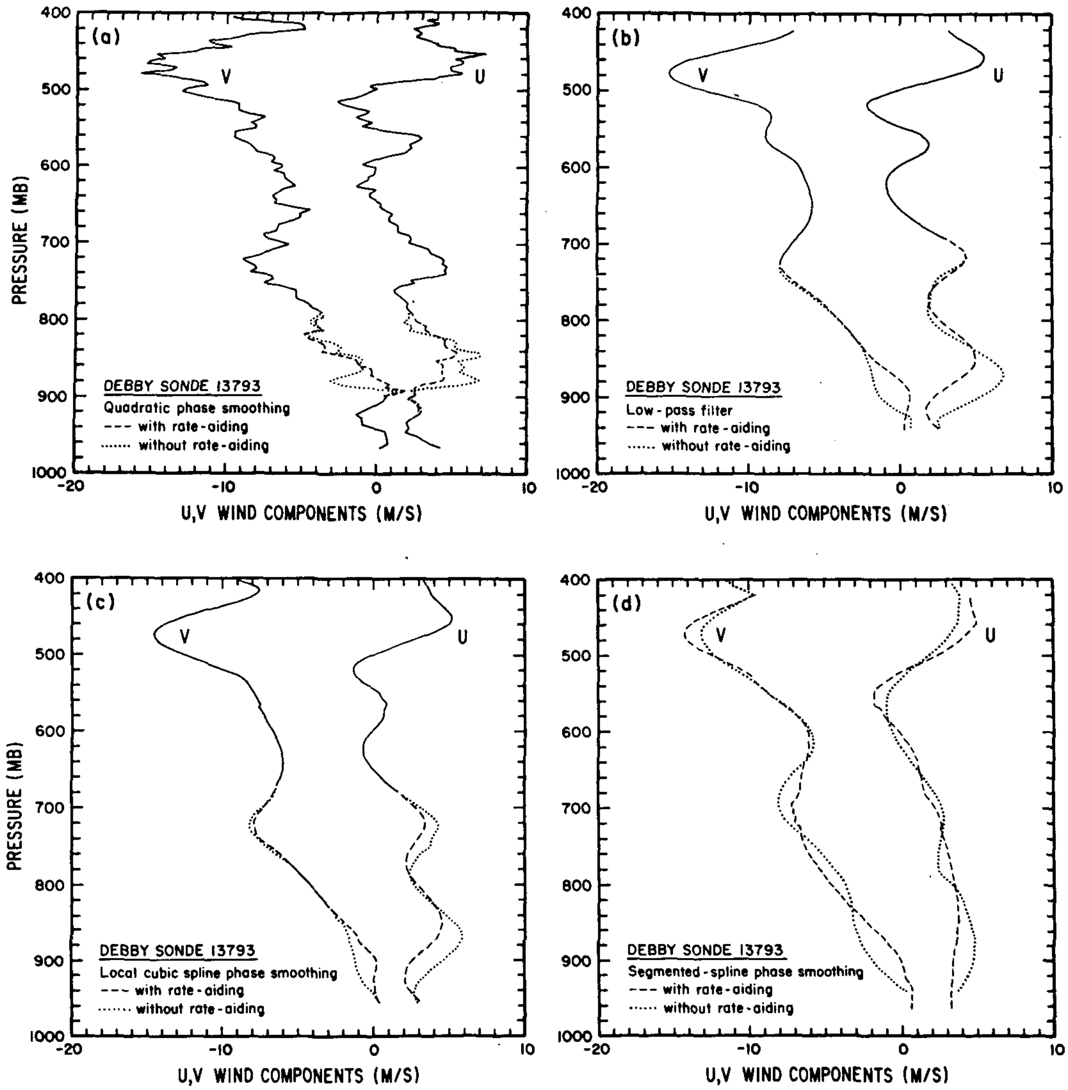

FIG. 2. Wind components u and v computed from an ODW dropped near 34.0°N, 70.1°W at 0114 UTC 16 September 1982, using (a) quadratic, (b) low-pass filter, (c) local cubic spline, and (d) segmented cubic spline phase-smoothing. The dashed line indicates winds computed from phase data normalized by rate-aiding. The dotted line indicates winds from phases that were not normalized. The aircraft was turning as the ODW fell from 830 to 870 mb.

nificant effect when the segmented spline smoother is used. The effect is not large, but is felt over a large portion of the sounding. The tentative conclusion reached by Franklin and Julian that the spline is insensitive to turns thus appears to be incorrect.

Even "phase-normalization" through rate-aiding does not seem to put the turns and legs on equal footing, as Table 5 indicates. Wind errors in turns remain higher than errors in legs, despite all efforts to reduce them. Curiously, the wind uncertainties (which measure noise and station geometry) are also larger in the turns. Unfortunately, aircraft navigational data were not archived for the 1982 flight to confirm this result. During a typical turning maneuver, the antenna is located behind the aircraft, relative to the sonde. This might account for the seemingly lower signal-to-noise ratios. Thus, although the techniques of phase-normalization and editing are very helpful, they do not entirely eliminate the effects of turns.

TABLE 5. Mean wind error and uncertainty (m s^{-1}) for 1985 stationary test ODW (normalized).

Smoother	Legs	Turns
Quadratic	1.42/1.35	1.87/1.57
Low-pass filter	1.17/1.36	1.50/1.56
Segmented spline	0.76/1.16	1.08/1.38
Local spline	0.99/1.47	1.29/1.66

4. Conclusions

A sophisticated and flexible technique for data smoothing developed by K. V. Ooyama has been modified for use in Omega windfinding. Two advantages of this procedure over methods currently being used are the reduction of representational distortion, and greater control over wind estimates near soundings' edges. The procedure has been "tuned" to give maximum vertical resolution for typical phase noise profiles. Those researchers interested in the spectral components of ODW atmospheric soundings may appreciate these advantages.

Wind measurement error during aircraft turns can be reduced by normalizing each phase profile with navigational track and ground speed information. Such "rate-aiding" shows that all phase-smoothing algorithms tested, including the Passi cubic-spline procedure, are susceptible to the effects of aircraft turns. The previous operational procedure of evaluating all stations' phase rates at a common time does not completely remove the effect of turns. A rate-aiding technique has therefore been added to the HRD ODW postprocessing procedures, which can improve ODW wind accuracy in turns by 2–3 m s^{-1}. Operational considerations frequently require changes in course of research aircraft while ODWs are in the air. Rate-aiding makes it possible to execute complicated flight patterns where necessary, without seriously impacting winds measured during such maneuvers.

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