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EXTENDED UHF RADAR OBSERVATIONS OF RIVER FLOW VELOCITY AND COMPARISONS WITH IN-SITU MEASUREMENTS

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Abstract: A RiverSonde radar system, operating at a frequency of approximately 350 MHz in the ultrahigh frequency (UHF) band, was installed on the Cowlitz River at Castle Rock, Washington, USA during October 2003 and has been operating for several months. Using techniques and equipment developed over several decades for measuring ocean surface currents at much lower frequencies, this radar system continuously measures the river streamflow from a location on one bank of the river by utilizing Bragg scattering from naturally-occurring water waves of 0.5-m wavelength. Data are processed in real time on a portable laptop computer and are available through a dial-up modem. The radar data provide hourly estimates of mean flow and cross-channel variations in the flow. Mean values of the radar flow profile track very closely continuous in-situ stage height measurements. River flow velocities of 0.8 $m \cdot s^{-1}$-3.5 $m \cdot s^{-1}$ were observed in the first five months of the experiment, with a nearly linear relationship between radar-inferred flow velocity and stage height of 9 m–14 m. The radar velocity also appears to have a weak correlation with the local wind and several tidal frequencies. The strong correlation between surface velocity and stage height suggests that – with refinement – surface velocity could replace stage height in river gaging, as well as offering additional flow information.

Keywords: Radar, Remote sensing, Non-contact velocity measurement

1 INTRODUCTION

From the earliest days of radar, echoes from water waves have been observed by radar systems. Crombie (1955) first identified the scattering mechanism as Bragg scattering by water waves having one-half the radar wavelength and traveling radially toward or away from the radar. Over the decades since then, radar systems have been developed to measure surface current velocity and wave energy. Because of the low propagation loss over salt water, most of these systems are used to remotely measure ocean surface currents out to 100 km or more from shore-based installations, using radar frequencies from 3 MHz to 30 MHz. Recently some radar systems have been utilized to measure fresh-water velocity on rivers by employing higher radar frequencies near 350 MHz, with correspondingly shorter wavelengths. Such a system, called RiverSonde (Teague *et al*., 2003), is described here.

A current-mapping radar system measures radial surface velocity by exploiting the Bragg scattering phenomenon. When observing a water surface, the strongest signals observed by the radar are generated by first-order scattering from the Bragg waves. In deep water (with a depth of at least one-quarter of the water wavelength), these waves have a phase velocity given by $v_p = \sqrt{(gL/2\pi)}$, where g is the gravitational acceleration and L is the water wavelength (equal to one-half the radar wavelength λ). Since the radar wavelength is known, the water wavelength and the Doppler shift $f_p = 2v_p/\lambda$ due to the water phase velocity also are known. The waves are advected by a mean flow velocity v_w, which produces an additional Doppler shift of $f_w = (2v_w/\lambda) \cos \theta$, where θ is the angle between the flow direction and the radar look direction. The total Doppler shift observed by the radar is just $f_t = f_p + f_w$ (Barrick *et al*., 1974). By measuring f_t and θ, and knowing f_p, it is possible to determine $v_w \cos \theta$.

The radar makes three basic measurements: the Doppler frequency f_t, the distance or range r to the scattering patch, and the direction of arrival θ of the radar echoes. From these, the radial component of the flow velocity can be mapped as a function of position on the water surface. If, in addition, the flow is assumed to be predominantly in one direction, as is often the case for a river, the total flow velocity and the cross-channel flow profile can be estimated.

2 COWLITZ RIVER EXPERIMENT

In order to evaluate the performance of a radar river flow measurement system, an experiment was started on 28 October 2003 and has continued for several months. The location is on the Cowlitz River at Castle Rock, Washington, USA, about 28 km from the confluence of the Cowlitz and Columbia Rivers, which is about 86 km from the west coast of Washington at the Pacific Ocean. The U. S. Geological Survey maintains a river gaging station at Castle Rock which provides stage height measurements every 15 min. In addition, on several occasions, the Geological Survey deployed several in-situ instruments to measure water depth using a ground-penetrating radar and the vertical and horizontal profiles of velocity using several acoustic instruments. Finally, two microwave radar systems were installed by the University of Washington at the same site. After the experiment was started, a weather station was added to the suite of instruments. The weather station records wind speed and direction, air temperature, barometric pressure, rainfall and humidity. Data from all of these systems eventually will be compared after the completion of the experiment. This paper will concentrate on the comparison of the RiverSonde measurements with the stage height and wind data from the first five months of the experiment.

Fig. 1 (a) RiverSonde Antenna. Energy is Transmitted on the Center Yagi and Received on all 3 Yagis. (b) River Sonde Equipment and Laptop Computer. The Weather-resistant Enclosure is Installed Inside a Storage Building

The RiverSonde system is installed in a shelter on one side of the river, with the antenna about 30 m from the near bank looking directly across the river. The river is about 78 m wide, with the far bank about 108 m from the antenna. The water depth was about 10 m at the start of the experiment. Radar data are recorded continuously and processed in hourly blocks on-site on a Macintosh laptop computer. Data are recorded to a local disk, and a dial-up modem provides remote access to both the data and the controlling programs. The weather data are recorded every ten minutes. The radar antenna system consists of three multi-element yagis, separated by one-half of the radar wavelength and oriented in different directions, with the outer yagis rotated 30° from the direction of the center antenna. This antenna configuration allows the direction of arrival of the radar echoes to be measured to a resolution of about 1° using MUSIC direction finding (Schmidt, 1986). The range resolution of the radar is set to 5 m, with a maximum range of 140 m. Transmitted power is less than 1 W. The antenna is shown in Fig. 1(a) and the radar equipment and computer are shown in Fig. 1(b).

3 RESULTS

The radar data are processed to determine the radial flow velocity at locations separated by 1° in angle and 5 m in range. An example of a radial vector map, averaged over an hour during a time of relatively calm conditions, is shown in Fig. 2. Data are plotted between the river banks. The vector field generally appears quite smooth, with some gaps which often appear at the same locations. It is believed that these gaps are due to partial blocking of the radar signals by trees along the near bank. There also is some variation in the coverage area due to the wind variability, especially on time scales of a few minutes. When the wind speed is very low, less than the 0.8 $m \cdot s^{-1}$ phase speed of the Bragg waves, there is little surface roughness from which to scatter the radar energy, but such calm conditions usually lasted for only brief periods each day, and rarely filled an entire hour.

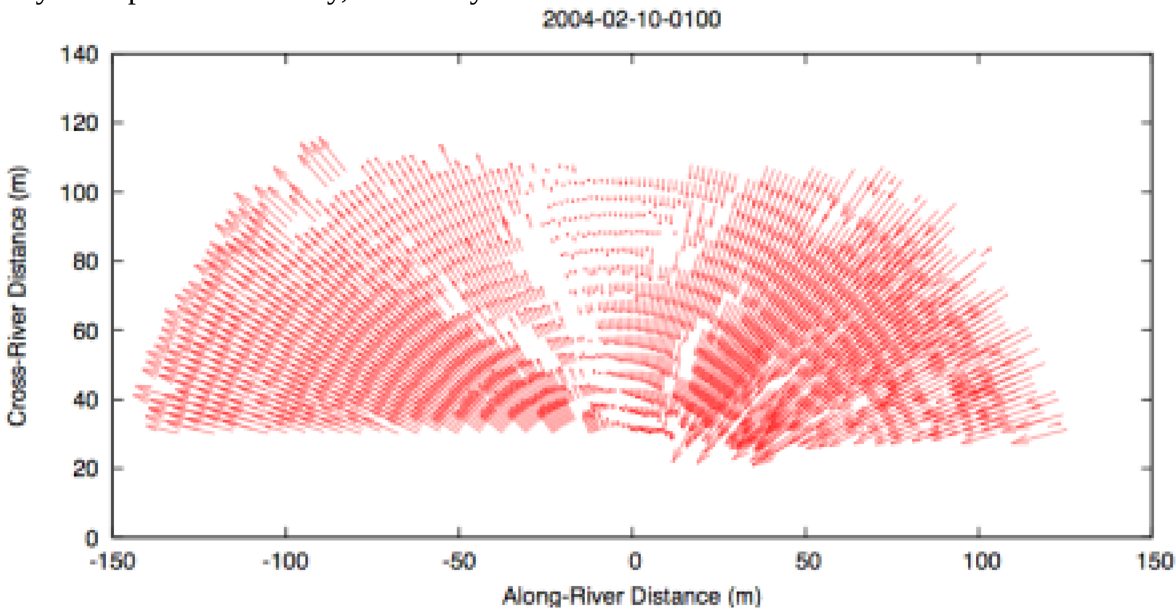

Fig. 2 Radial Flow Vectors Averaged Over One Hour on 10 February 2004. Vectors are Plotted Between the River Banks with 1° Resolution in Angle and 5 m in Range.A Velocity of 1.0 $m \cdot s^{-1}$ is Plotted with an Apparent Length of 10 m

After computing the radial vectors, the cross-channel flow profile is estimated. To make this estimate, it is assumed that the flow is essentially parallel to the mean direction of the channel. The mean flow direction is estimated by noting the azimuthal direction for which the radial velocity is zero. For example, in Fig. 2, this direction is about 8° counter-clockwise from the antenna broadside direction. The mean flow direction is assumed to be perpendicular to this direction. The water surface is divided into 5-m strips parallel to the estimated mean flow direction, and the mean flow in each strip is computed as a least-squares fit to all the available radial vectors within that strip, assuming a $v_w \cos \theta$ projection of the river flow vector on the radar look direction. An example of the estimated cross-channel profile, for the radial data of Fig. 2, is shown in Fig. 3. The mean of the velocity estimate in each strip is plotted with a dot, the standard deviation of the estimates within the strip is shown by the error bars, and the median of the estimates is indicated by the asterisk. The median value is less sensitive to outlying data points than the mean and is used in the subsequent processing. Estimates of cross-channel profiles are made hourly along with the radial vector maps.

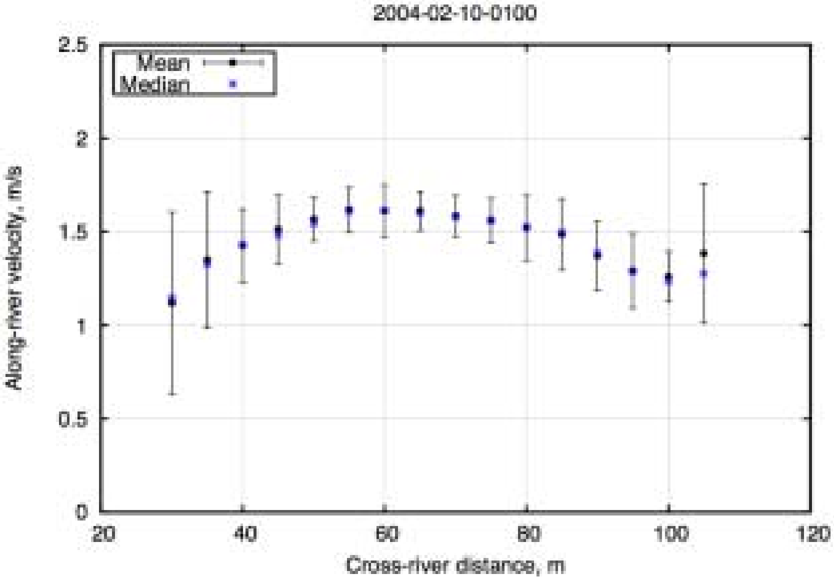

Fig. 3 Cross-channel Velocity Profile at 10 February 2004 at 0100 PST. Velocity is Estimated at 5-m Intervals Across the Channel. The Mean Estimate from all Radial Vectors within each 5-m Strip in the Flow Direction is Indicated by the Dots, the Standard Deviation is Indicated by the Error Bars,and the Median Estimate is Indicated by the Asterisks

Finally, a single mean velocity estimate for each hour is made by calculating the mean of the cross-channel median velocity estimates over the strips from 40 m to 80 m from the radar antenna, for which the flow generally is stable and the radar signals are strong. A time series of the mean velocity estimates for a two-week period is shown in Fig. 4, along with the river stage height data and hourly wind vectors. The relative scales of the radar velocity and water height have been adjusted based on a least-squares fit between radar velocity and water height. The agreement between the radar velocity and water height is immediately apparent. Using the Regress function of Mathematica, a linear regression of radar velocity on water height alone yielded a model coefficient of determination R^2 of 0.926. Including the square of the water height and the along- and cross-channel wind raised the model R^2 to 0.933.

Also obvious is a roughly periodic variation in the radar velocity, on the order of 10 cm·s^{-1}, which does not seem to be reflected in the height data. (Note that there are rapid jumps in the height curve, indicating that the height measurements were done with sufficient bandwidth to pass signals with periods of a few hours.) Initially it was suspected that periodic variations in wind velocity might be responsible, as the radar is sensitive to water velocity at the topmost 3cm or 4 cm of the water column (Stewart and Joy, 1974) which is strongly coupled to the wind. Indeed, that suspicion prompted the installation of the weather station. However, from Fig. 4 there appears to be little correlation between the wind vectors and the periodic radar signal. A Fourier time-series analysis was applied to the radar data from 2 February to 22 March, interpolating across occasional gaps of one to three hours. A plot of the resulting power spectrum is shown in Fig. 5. This figure represents a single transform, so it is noisy, but several distinct peaks are evident, especially near 1 and 2 cycles·day^{-1}, with additional peaks near 0.5 cycle·day^{-1}. The peaks at 1 and 2 cycles·day^{-1} suggest that some of the periodic signal in the radar velocity data may have frequencies matching tidal frequencies. Consequently, a set of tidal components consisting of the M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, M_4, MS_4, MF and MM terms (Pond and Pickard, 1989, ch. 13) was added to the model. Recalculating the linear regression yielded a model R^2 of 0.936. As expected from Fig. 5, the largest contributions to the model variance came from the diurnal and semi-diurnal components, but their combined contribution to the model R^2 was only 0.002,5, compared to 0.926 for the linear height term. With the 87-day duration of the radar velocity time series, it was difficult to distinguish among several closely-spaced components. Nevertheless, the effect of their inclusion can be seen in Fig. 6, which shows the radar data, the prediction from height and wind terms alone, and the prediction from the full model. The inclusion of the tidal components clearly models the periodic variations in the radar velocity, although there is some residual error left. Some of the errors may be due to the omission of any energy at the three peaks near 0.5 cycle·day^{-1} in Fig. 5 which do not correspond to common tidal components. Fig. 6 shows a 10-day data segment, but the predicted functions were calculated based on the entire 87-day radar record, and the phase relations between the radar data and the predictions suggest a strong phase coherence over the entire record.

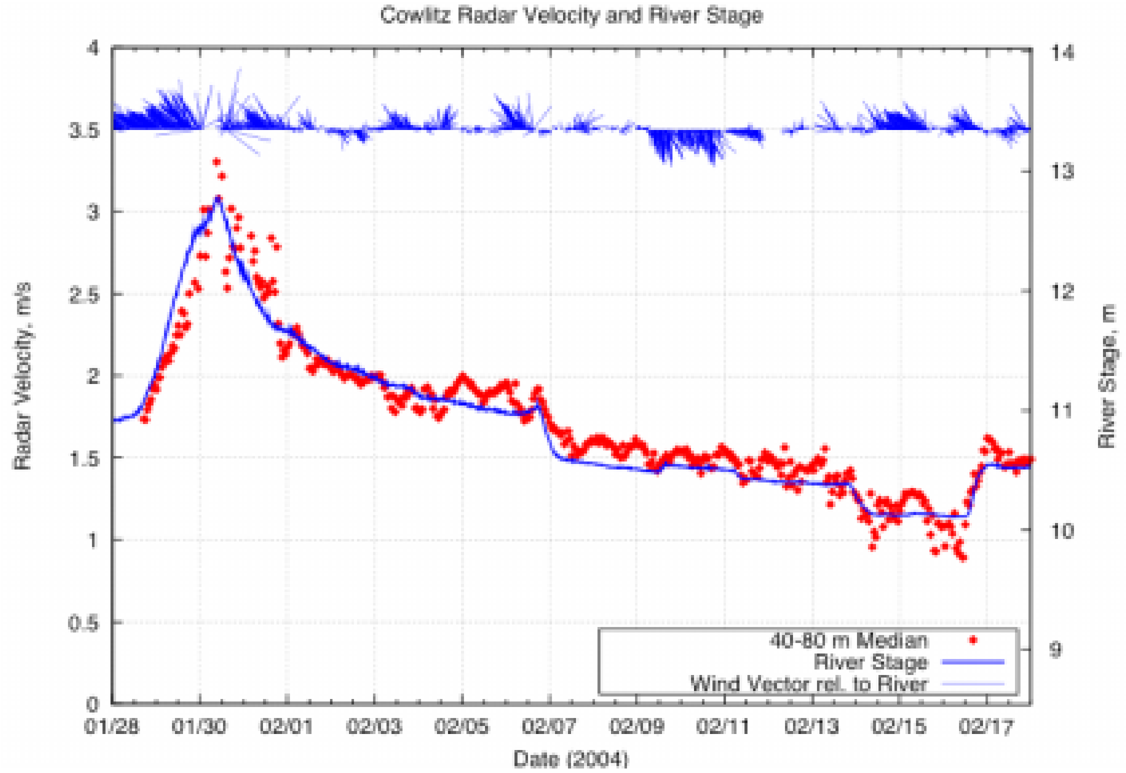

Fig. 4 Time Series of Radar Velocity (points), River Stage Height (solid line), and Wind Victors for 28 January to 18 February 2004. Wind Vectors Rertically Upward Indicate Flow Upstream (Opposing the Water Flow)

4 DISCUSSION

The RiverSonde system has been in nearly continuous operation at Castle Rock for at least five months since its installation on 28 October 2003, except for about two weeks during the early part of the experiment. During the course of the experiment, the stage height varied from about 9 m to 14 m, and the flow velocity varied from about 0.8 to nearly 3.5 m·s^{-1}. Over that range, there has been a very high correlation between radar-inferred flow velocity and measured river stage height, with an R^2 value of at least 0.93. The influence of the wind has been very small, on the order of 1 cm·s^{-1} or less, but there are periodic variations on the order of 10 cm·s^{-1} which have frequencies similar to the dominant diurnal and semi-diurnal tidal frequencies. Both the stage height and water velocity at the confluence of the Cowlitz and Columbia Rivers are strongly influenced by the tide, with dominant components of K_1 (23.93 h) and M_2 (12.42 h), so it is not surprising to see a signature at tidal frequencies at Castle Rock. However, this signature does not seem to be present in the Castle Rock stage height data. There also appear to be some frequency components near 0.5 cycles·day^{-1} which are not obviously related to the common tidal constituents.

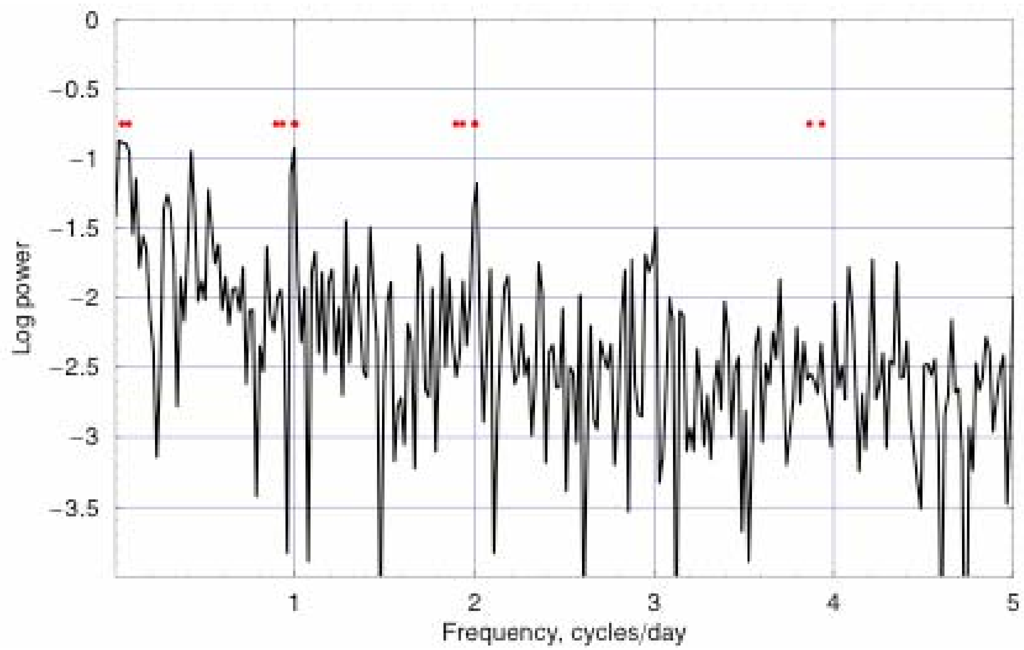

Fig. 5 Power Spectrum from a Single Fourier Transform of the Radar Velocity time Series of Fig. 4 from 2 February to 22 Mar 2004. Positions of Several Dominant Tidal Frequencies are Indicated by Red Dots.

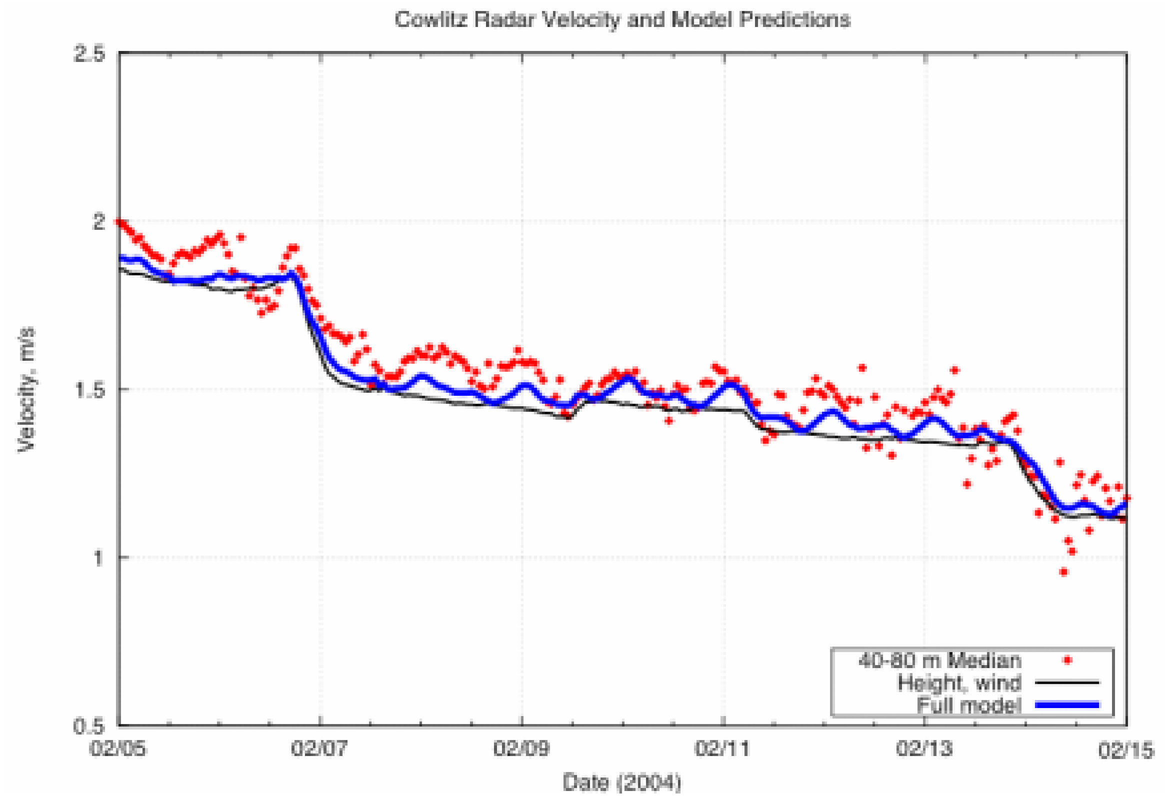

Fig. 6 Comparison of a 10-day Sequence of Radar Velocity Data (red points), a Model which Includes only Height and wind terms (thin black line), and a model which includes height, wind and tidal terms (thick blue line)

After some initial adjustment of the processing algorithms, the data processing is completely automatic, and data are available within an hour of their collection via a dial-up modem connection. All data, including the raw measurements, are archived to disks in case subsequent reprocessing is desired. The strong correlation between radar-inferred surface velocity and river stage height suggest that the RiverSonde may be attractive for routine monitoring of medium-sized rivers. The experiment should be repeated at different locations to explore any environmental influences.

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