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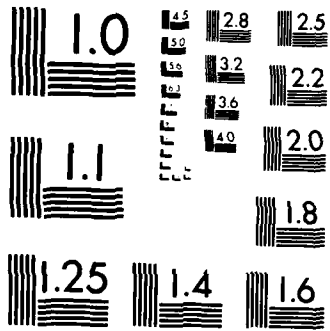
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM	
1. REPORT NUMBER JSR-84-203A	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Second Order Bragg Scattering in a SAR		5. TYPE OF REPORT & PERIOD COVERED	
		6. PERFORMING ORG. REPORT NUMBER	
7. AUTHOR(s) R. Davis		8. CONTRACT OR GRANT NUMBER(s) F19628-84-C-0001	
		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	
9. PERFORMING ORGANIZATION NAME AND ADDRESS The MITRE Corporation 1820 Dolley Madison Blvd. McLean, VA 22102		12. REPORT DATE August 1984	13. NO. OF PAGES 6
11. CONTROLLING OFFICE NAME AND ADDRESS		15. SECURITY CLASS. (of this report) Unclassified	
14. MONITORING AGENCY NAME & ADDRESS (if diff. from Controlling Office)		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this report) <div style="text-align: center; border: 1px solid black; padding: 5px;">DISTRIBUTION STATEMENT A Approved for public release Distribution Unlimited</div>			
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from report)			
18. SUPPLEMENTARY NOTES			
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)			
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report discusses why narrow lines are seen from second order Bragg scattering.			

Second Order Bragg Scattering in a SAR

R. Davis

August 1984

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SECOND ORDER BRAGG SCATTERING IN A SAR

Why might we see narrow lines from second order Bragg scattering?

If we accept the notion that the short-wave components of the ship wake are slightly distorted versions of the Kelvin wake, then there is the possibility of scattering, at a given place, from a spectrum of waves. The Dabob Bay data indicates that there is little energy in the wake having wave numbers capable of producing first-order Bragg scattering of L-band radar. This could be taken as explaining why even narrower V wakes are not observed. But the observations do show considerable enhancement of waves of twice the Bragg wavelength at the angle where a SAR wake is observed.

Second order Bragg scattering involves interaction of the radar wave, with horizontal wavenumber r , and two sinusoidal surface wave components with wavenumbers k and $2r-k$ which add to $2r$ (the usual Bragg wavenumber is $2r$). Thus a wide range of surface waves could contribute to scattering. Is this then apt to produce a locally concentrated return such as is observed? The following little model suggests that it will.



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Rather than deal with a synthesized aperture, we consider a real aperture radar in which the spatial resolution is obtained by antenna pattern, but additional frequency filtering is applied. This filtering is our lazy-man's analog of the frequency filtering used to synthesize azimuth aperture.

Over a patch of the size of the radar aperture the surface height may be represented as

$$\eta(\underline{x}, t) = \sum_{\underline{k}} a(\underline{k}) e^{i \underline{k} \cdot \underline{x} - i \omega(\underline{k})t}, \quad |\Delta k| = \frac{(2\pi)^2}{\text{aperture}}$$

Nonlinear hydrodynamic wave interactions are neglected by taking the waves to obey the dispersion relation $\omega^2(\underline{k}) = g|\underline{k}|$.

The first and second order scattering mechanisms provide a radar signal of the form (from Appendix B1, Eqs. (18a, b))

$$S(t) = e^{i\omega_r t} (2r_v)^2 a(2\underline{r}) e^{-i\omega(2\underline{r})t} \\ + e^{i\omega_r t} (2r_v)^2 \sum_{\underline{k}} 2 \sqrt{r^2 - k^2} a(\underline{r} + \underline{k}) a(\underline{r} - \underline{k}) e^{-i\omega(\underline{r} + \underline{k})t - i\omega(\underline{r} - \underline{k})t}$$

First order Bragg scattering selects the wave component with wavenumber $2\underline{r}$ while second order scattering involves pairs of waves

whose wavenumbers $\underline{r} + \underline{k}$ and $\underline{r} - \underline{k}$ sum to $2\underline{r}$. Here ω_r is the radar frequency and r_v is the vertical component of radar wavenumber.

Now suppose the radar signal is filtered at frequency $\omega_r + \omega_o$ and the energy of the filtered signal is recorded. The filtered signal is $\frac{1}{2T} \int_{-T}^T e^{i(\omega_r + \omega_o)t} S(t) \equiv \hat{S}(\omega_o)$

$$\hat{S}(\omega_o) = 4 r_v^2 a(2\underline{r}) \frac{\sin [\omega_o - \omega(2\underline{r})] T}{[\omega_o - \omega(2\underline{r})] T} + 8 r_v^2 \sum_{\underline{k}} a(\underline{r}+\underline{k}) a(\underline{r}-\underline{k}) \sqrt{r^2 - k^2} \frac{\sin [\omega_o - \omega(\underline{r}+\underline{k}) - \omega(\underline{r}-\underline{k})] T}{[\omega_o - \omega(\underline{r}+\underline{k}) - \omega(\underline{r}-\underline{k})] T}$$

The first order contribution to average signal power, σ^2 is maximized when $\omega_o = \omega(2\underline{r})$ and has magnitude

$$\sigma_1^2 = 16 r_v^4 |\Delta \underline{k}| \Psi(2\underline{r}) \quad (1)$$

where Ψ is the ocean height wavenumber spectrum. If we imagine that the high wavenumber wake is not well collimated, but still propagates at the group velocity, this return will be found near the wake angle $\theta_1 = C_g(2\underline{r})/U$, where U is the ship speed. Wakes are not seen at this narrow angle. We hypothesize, from the Dabob Bay measurements, that little of this energy is generated or it quickly dissipates.

The second order contribution is σ^2 is

$$\sigma_2^2 = 64 r_v^4 \sum_{\underline{k}} \langle |a(\underline{r}+\underline{k})|^2 \rangle \langle |a(\underline{r}-\underline{k})|^2 \rangle [r^2 - k^2] \left[\frac{\sin \phi(\underline{k})}{\phi(\underline{k})} \right]^2$$

$$\phi(\underline{k}) = [\omega_0 - \omega(\underline{r}+\underline{k}) - \omega(\underline{r}-\underline{k})] T$$

$$\sigma_2^2 = 64 r_v^4 |\Delta \underline{k}| \int d\underline{k} \Psi(\underline{r}+\underline{k}) \Psi(\underline{r}-\underline{k}) [r^2 - k^2] \left[\frac{\sin \phi(\underline{k})}{\phi(\underline{k})} \right]^2$$

By adjusting the filter frequency, ϕ can be made to vanish for any specified \underline{k} . The resulting mean square intensity will depend on both Ψ and the area of \underline{k} space over which $\frac{\sin \phi}{\phi}$ remains of significant size. The largest area of integration occurs when $\nabla_{\underline{k}} \phi = 0$ which occurs at $\underline{k} = 0$. Thus the strongest return will be from ocean waves of wavenumber \underline{r} , half the first order Bragg wavenumber. The return from this neighborhood of wavenumbers is enhanced because \underline{r} is a saddle-point of the function ϕ . The return depends on $T\sqrt{gr}$, frequency of the $\underline{k} = \underline{r}$ wave times half the integration time. Assuming Ψ is relatively uniform near \underline{r} and taking $T\sqrt{gr} = 10$

$$\sigma_2^2 = 173 r_v^4 |\Delta \underline{k}| r^4 \Psi^2(\underline{r}) \quad (2)$$

The Dabob Bay slope measurements (after conversion from frequency to the wavenumber component, k_1 , parallel to the ENDEAVOR's course) provide

$$\psi_1(k_1) = \int dk_2 \psi(k) k_1^2$$

Assuming an angular spread of $\pm \frac{\pi}{6}$ for these waves,

$$\psi_1(k) \approx \frac{\pi}{3} k_1^3 \psi(k)$$

At $k_1 \approx 2\pi/30$ cm, corresponding to $2r$ of the L-Band SAR,

$\psi_1 \approx 10^{-3}$ m, shows no change with wake angle, and appears everywhere to be a background noise level. The maximum $\psi_1(r)$ is found near $\theta = 3.5^\circ$ (where SAR return is found) and is of the order 5×10^{-2} m.

The ratio of second to first order Bragg return is, for $T\sqrt{gr} = 10$,

$$\begin{aligned} \frac{\sigma_2^2}{\sigma_1^2} &= \frac{173 r^4 \psi^2(\underline{r})}{16 \psi(2\underline{r})} = \frac{173}{16} 8r \frac{\psi_1^2(r)}{\psi_1(2r)} = 10^2 10m^{-1} \frac{(5 \times 10^{-2})^2 m^2}{10^{-3} m} \\ &= 10^3 \end{aligned}$$

Thus, to the extent that the frequency-filter model proposed here adequately mimics SAR processing, one would expect to see the second order signal much more strongly than the first order signal. The second order signal will be seen where wake energy is concentrated near wavenumber $k = r$, that is aligned with the radar look angle and with wavelength twice the linear Bragg wavelength.

Why is second order return so strong? There are two points to the answer. First, observations show that the energy density increases rapidly as wavenumber decreases. Second, the second order return is amplified because the scattering mechanism allows contributions from a neighborhood of $\underline{k} = \underline{r}$ whereas the first order mechanism selects $\underline{k} = 2\underline{r}$. The development here differs from that in B1 in two ways. First, the surface waves are taken to fill a spectrum of energy rather than being a well defined classical Kelvin wake. Second, we seek the special effect of frequency filtering such as is used to synthesize the azimuth aparative in a SAR. The strong enhancement of second order Bragg is dependent on these assumptions - it depends on aperture synthesis and the existence of wave energy throughout the \underline{k} neighborhood of \underline{r} .

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