Effect of Long Waves on Ku-Band Ocean Radar Backscatter at Low Incidence Angles Using TRMM and Altimeter Data

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***Abstract*—This letter uses a large ocean satellite data set to document relationships between Ku-band radar backscatter (σ_0) of the sea surface, near-surface wind speed (U), and ocean wave height (SWH). The observations come from satellite crossovers of the Tropical Rainfall Mapping Mission (TRMM) Precipitation Radar (PR) and two satellite altimeters, namely: 1) Jason-1 and 2) ENVISAT. At these nodes, we obtain TRMM clear-air normalized radar cross-section data along with coincident altimeter-derived significant wave height. Wind speed estimates come from the European Centre for Medium-Range Weather Forecast. TRMM PR is the first satellite to measure low incidence Ku-band ocean backscatter at a continuum of incidence angles from 0° to 18°. This letter utilizes these global ocean data to assess hypotheses developed in past theoretical and field studies.**

***Index Terms*—Altimetry, radar cross section, scattering, spaceborne radar.**

I. Introduction

TWO now-standard satellite systems for ocean wind estimation are the altimeter and the scatterometer. The former views the sea from a downlooking ($\theta = 0°$) incidence angle, whereas the latter uses side-looking angles from 20° to 60°. It is widely held that centimeter-scale ocean gravity-capillary waves and their growth or decay with wind forcing are the dominant controls of the radar backscatter cross section (σ_0) variation for both sensors, but the ocean reflection is distinctly different for these two systems which is consistent with the optical expectation; increased wave roughness decreases altimeter σ_0 but increases it for the scatterometer. Regardless of such differences, the linkage between σ_0 and wind forcing is used for both sensors to empirically derive wind speed inversion algorithms that are well validated and widely used. However, long-wavelength tilting of short-scale waves is a known effect inducing fundamental perturbations in the precise relationship between local wind forcing and local radar backscatter variations. A substantial fraction of the longer tilting gravity wave field is due to swell and wind seas generated by distant or turning winds, which are uncoupled and misaligned with the local wind.

Previous investigations have used bulk wave statistical parameters such as significant wave height (SWH) to demonstrate long-wave variability impacts upon σ_0 [12], [13], [17] and more widely on retrieved winds [5], [6], [11], [15], [16]. Such observations have clearly shown long-wave effects on altimeter backscatter and have led to the development of an operational wind speed model for the satellite altimeter that utilizes both σ_0 and SWH [6], where fortuitously both measurements are made from the same platform. SWH is not retrievable using scatterometry.

While altimeter ocean backscatter has been successfully modeled with quasi-specular scattering theory, off-nadir radar backscatter represents a mixture of specular and tilted Bragg resonance diffraction processes as the incidence angle extends away from 0° out toward 10°–15°. The transition between the two scattering regimes depends upon the instrument wavelength and the wind speed and has been proposed to occur near an incidence angle of 10°. A notable observation is that close to this angle a lower sensitivity between σ_0 and wind speed is found [7]. This particular feature has been exploited over the ocean to calibrate airborne and spaceborne precipitation or cloud radars—the objective being to minimize uncertainty due to surface wind variations.

The low, or near-nadir, incidence angle range of $1° \leq \theta \leq 18°$, is currently covered by the Precipitation Radar (PR) on the Tropical Rainfall Mapping Mission (TRMM) [9], [10]. Though designed specifically for the measurement of precipitation profiles in the atmosphere over both land and ocean, the PR system also acquires sea surface σ_0 under rain-free conditions. This is the first and only satellite system that provides such angle-resolved scattering near nadir, and the objective here is to further examine these data to help bridge what is known regarding the effects of waves on the altimeter and scatterometer. In this letter, we take the advantage of a large collocated database, which is compiled using PR and both Jason-1 and ENVISAT altimeters, to extend the description of PR σ_0 in terms of incidence angle, wind speed, and significant wave height through a tabulated model function $\sigma_0(\theta, U, \mathrm{SWH})$. This provides a compact and statistically accurate representation permitting the study of the expected wave tilting impacts on the sea surface scattering at these low incidence angles.

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II. DATA SETS

A. TRMM PR Cross Section

The TRMM satellite was launched in November 1997 carrying five instruments including the PR. Since the focus of TRMM is to measure rainfall in the tropics, a low inclination non-sun-synchronous orbit was selected to confine the satellite ground track between 35° S and 35° N. The PR is a Ku-band pulsed radar operating at 13.8 GHz and horizontal polarization. The PR antenna is an electronically scanned phased array that scans a plane normal to the flight direction (cross-track) through the nadir with measurements at 49 beam positions (e.g., the angle bins 1, 25, and 49 correspond to the incidence angles $+18°$, 0.1°, and $-18°$, respectively) over a 215-km ground swath. The scan duration is equal to 0.6 s with a surface pixel provided every 4.3 km both along and cross-track [8], [9] for the original orbit height.

The TRMM orbit was raised from 350 to 403 km in August 2001 to increase the duration of the mission. The spatial resolution of the PR is thus degraded slightly, increasing to 5.0 km by 5.0 km. Our data analysis covers the one-year period of 2003. The high quality of the PR surface ocean σ_0 data for this period was confirmed in two recent studies [4], [18]. The data product used herein is TRMM PR standard product 2A21 (ver. 5) from the Goddard Distributed Active Archive Center. These data include normalized radar cross-section measurements, associated quality flags, and a rain/no-rain flag for each incidence angle bin or pixel [10]. Data over land, with any data quality issue, or with rain over the ocean target are all excluded from the composite data set. Further data processing and satellite-to-satellite crossover selection details follow [18] except that for this letter the search was performed over all incidence angles in the PR ground tracks. As shown in the previous study, the density of crossovers increases with latitude due to the combined altimeter–PR orbit characteristics.

B. Wind Speed and Significant Wave Height Data

We use surface wind speed estimates (U) from the surface model analysis provided by the European Centre for Medium-Range Weather Forecast (ECMWF) as a common reference to quantify PR σ_0 wind dependence. SWH data for the study come from the Jason-1 and ENVISAT altimeters. The potential negative impact of using the model wind products is that these data are extracted and interpolated from six hourly 1° grid data set and that model winds will always disagree with *in situ* measurements to a certain degree. Thus, the model functions to be developed will be slightly impacted, particularly at lightest wind speed, by this interpolation but previous studies (e.g., [6]) have shown that the systematic nature of wave height impacts should still be quite apparent and similar when using the ECMWF model winds and it is this impact that is the main focus of this letter. While one could go another step to gather TRMM/scatterometer/altimeter triplet crossovers to replace ECMWF winds with those from scatterometry, this step dramatically reduces the data set size without dramatically increasing the quality of the result as the agreement between the ECMWF and scatterometer product is high.

Time/space interpolated ECMWF wind speed and altimeter SWH estimates are both available in the Geophysical Data Records (GDR) for these two altimeters. The Jason-1 altimetric mission was launched in December 2001 and placed in the same ground track as its predecessor TOPEX/Poseidon. It carries the Poseidon-2 altimeter that was derived from the experimental Poseidon-1 instrument aboard TOPEX/Poseidon. The satellite flies a non-sun-synchronous orbit at an altitude of 1336 km with an inclination of 66°. The ENVISAT altimeter was launched on March 2002 and is derived from the European Remote Sensing satellite (ERS)-1 and ERS-2 altimeters. The satellite orbit is sun-synchronous at an altitude of 800 km with an inclination of 98.55°. Parameters from both Jason-1 and ENVISAT GDRs over the one-year period of 2003 are used for this letter. Erroneous altimeter estimates are discarded using conventional data quality flagging. Further data filtering follows from the Cal/Val quality assessment that is routinely performed at the Collecte Localisation Satellites [2]. We use only rain-free data.

C. Crossover Selection

The criteria used for the collocation between PR and Jason-1 or ENVISAT crossovers are given as follows: time separation within 1 h and spatial separation less than 100 km. The different collocation sets PR/altimeter/ECMWF are limited in latitude to the tropics within $\pm 35°$ of the equator due to the TRMM orbit. We merge the two data sets using, respectively, Jason-1 and ENVISAT SWH estimates to obtain a unique data set over which the geophysical model function $\sigma_0(\theta, U, \mathrm{SWH})$ can be produced. To insure homogeneity and consistency between altimeter SWH estimates for the two missions, we applied small $[O\ (\mathrm{cm})]$ SWH adjustments [14].

III. NEAR-NADIR SCATTERING MODEL

Following a standard quasi-specular backscattering approach, near-nadir σ_0 can be written as

$$\sigma_0(\theta, U, \mathrm{SWH}) = \frac{\rho(U)}{\mathrm{mss}(U, \mathrm{SWH})} \sec^4(\theta) \exp\left[-\frac{\tan^2(\theta)}{\mathrm{mss}(U, \mathrm{SWH})}\right] \quad (1)$$

where σ_0 is the normalized backscatter in natural units (not in decibels), and θ is the incidence angle as previously defined. ρ represents an effective nadir reflection coefficient, and mss is a measure of the effective surface mean square slope [21]. The model assumes that sea state dependence of ρ is unlikely or negligible, which is verified to a large extent using the dual frequency capabilities of the TOPEX altimeter [1], [3]. The model also allows for the impact of sea state on the cross section. It is the overall degree of sea state development, which contributes to the mean squared tilting slopes.

As obtained in Fig. 1(a) (see also [4, Fig. 5]), the Gaussian assumption of (1) is qualitatively consistent with the PR data

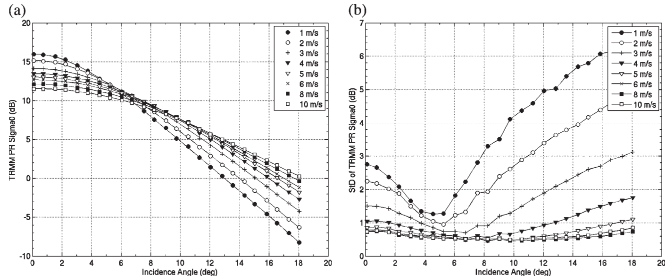

Fig. 1. (a) Mean values and (b) standard deviations of binned PR σ_0 as a function of incidence angle for different wind speeds (SWH between 0.5 and 6.5 m).

up to about 18°. Observed biases at nadir between altimeter measurements and PR data can be attributed to absolute calibration issues [18]. According to (1), analysis of a single-frequency radar altimeter with both wind speed and sea state proxy cannot, with certainty, separate the dependencies related to mss variations from those related to variations of ρ.

The differentiation of (1) with respect to mss yields

$$\frac{\partial \sigma_0}{\partial \mathrm{mss}} = \frac{\tan^2(\theta) - \mathrm{mss}}{\mathrm{mss}^2}\sigma_0. \tag{2}$$

The form of the fractional cross-section variation $(\Delta\sigma_0/\sigma_0)$ in natural units (not in decibels), due to fractional change of mss, will be incidence angle dependent, i.e., 1) when $\tan^2(\theta) <$ mss, $\Delta\sigma_0/\sigma_0 \propto (-\Delta\mathrm{mss}/\mathrm{mss})$ and the nadir viewing altimeter falls in this category, and 2) at higher incidence angles, when $\tan^2(\theta) >$ mss, $\Delta\sigma_0/\sigma_0 \propto (+\Delta\mathrm{mss}/\mathrm{mss})$ and the off-nadir viewing scatterometer falls into this category. The following analysis of the PR σ_0 documents this fractional change of σ_0 with incidence angle.

IV. Analysis of PR Backscatter

A. *Geophysical Model Function for Ku-Band Ocean σ_0 at Low Incidence Angles*

We restrict this letter to light-to-moderate wind speed conditions up to 11 m/s. At wind speeds above this range, complex nonlinear surface wave structure and foam involved with large-scale wave breaking become critical to the surface description and the radar scattering from it. While these higher winds are important, the extensive amount of data that fall at or below 11 m/s and the physics associated with these conditions are the focus of this letter. Two empirical tabular model functions are developed. The first model is based on the analysis of measured σ_0 at each PR incidence angle within specified wind speed intervals and is denoted $\sigma_0(\theta, U)$. The 25 different incidence angles are from 0.1° to 18.05°, and the bin width is about 0.1°. The model is formed from the sample mean σ_0 in each 1-m/s wind speed and incidence angle 2-D bin. A 3σ filter is then applied to eliminate outlier measurements, giving Fig. 1(a). The second model function takes into account both wind speed and significant wave height dependence at each incidence angle. It is denoted as $\sigma_0(\theta, U, \mathrm{SWH})$. The wind speed bin width is still 1 m/s, and the SWH bin width is set to 1 m.

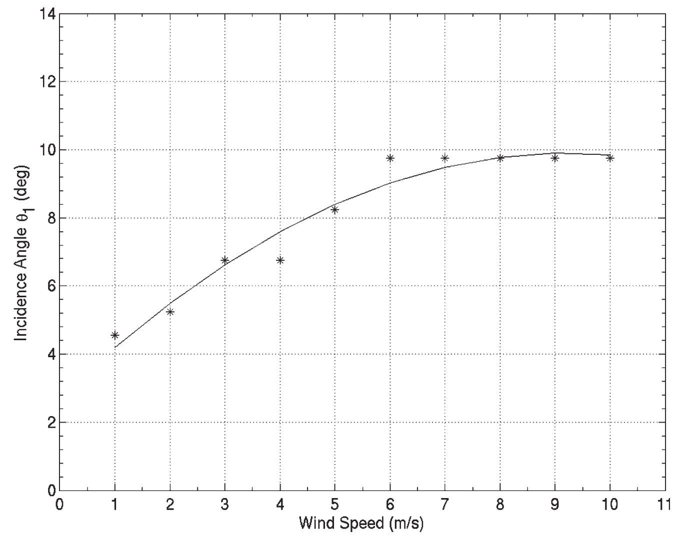

Fig. 2. Incidence angle θ_1 presenting the lowest standard deviation of binned PR σ_0 at a given wind speed as function of wind speed. Overlaid is a quadratic regression fit to better display the trend.

B. $\sigma_0(\theta, U)$

Fig. 1(a) shows that results from nadir to 5° in incidence angle are monotonically decreasing in σ_0 as wind speed increases. Above 10°, σ_0 becomes a monotonically increasing function of wind speed. In the range $5^\circ \leq \theta \leq 10^\circ$, σ_0 first increases, then decreases with increasing wind speed with a low sensitivity to wind speed. The standard deviations of the σ_0 measurements in each (θ, U) bin are shown in Fig. 1(b) with respect to incidence angle for different wind speeds. For all wind speeds, standard deviations reach a minimum value at an incidence θ_1 between 4° and 10°. Higher magnitudes of standard deviation are associated with light wind speeds, and these magnitudes decrease with increasing wind speed. Magnitudes are smaller at nadir (0.1°) than at 18° for light wind speeds up to 5 m/s. Above 5 m/s, results show similar values. In the range $4^\circ \leq \theta \leq 10^\circ$, σ_0 not only exhibits low sensitivity to wind speed but also an overall low variability. This lowered variability is related to (2). The angle θ_1, in Fig. 2, roughly identifies the condition $\tan^2(\theta) = \mathrm{mss}(U)$ for which the fractional cross-section variation is minimum, and the shift of θ_1 with wind speed corresponds to the anticipated increase of mss. As found, there is an increase of θ_1 with increasing wind speed up to 7 m/s followed by a saturation trend toward ~10° for higher moderate winds.

C. $\sigma_0(\theta, U, SWH)$

The very large collocated data set compiled enables the analysis of the combined incidence angle and SWH dependencies on σ_0 using the narrow 1-m/s wind speed bin. Fig. 3 displays a difference factor δ defined as $[\sigma_0(\theta, U, \mathrm{SWH}) - \sigma_0(\theta, U)]$, in decibels, with respect to incidence angle at four selected wind speeds of 2, 5, 7, and 10 m/s. For all winds, behavior of δ as a function of SWH is clear. At low SWH (~1 m) representing young sea, δ decreases with increasing angle, whereas for higher SWH (~4 m associated mostly with

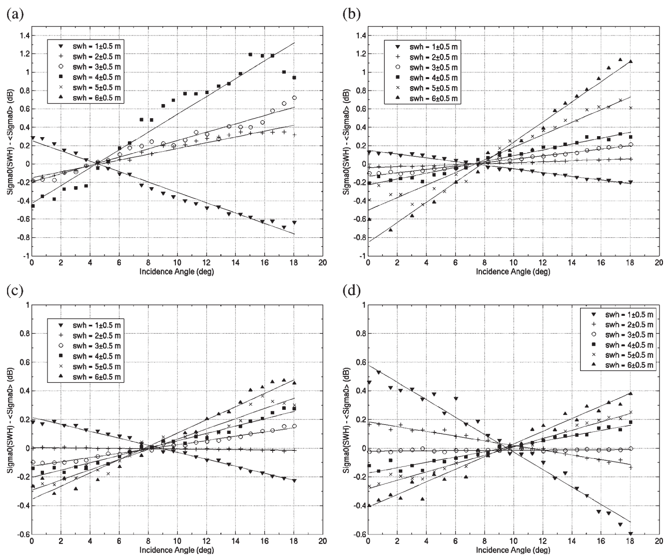

Fig. 3. Difference δ (between averaged PR σ_0 associated to a 1-m class of SWH and the averaged values estimated over all SWH) as function of incidence angles for various SWH classes at selected wind speeds: (a) 2 m/s, (b) 5 m/s, (c) 7 m/s, and (d) 10 m/s (1-m/s bin width). Overlaid are linear regression fits to better display the trends.

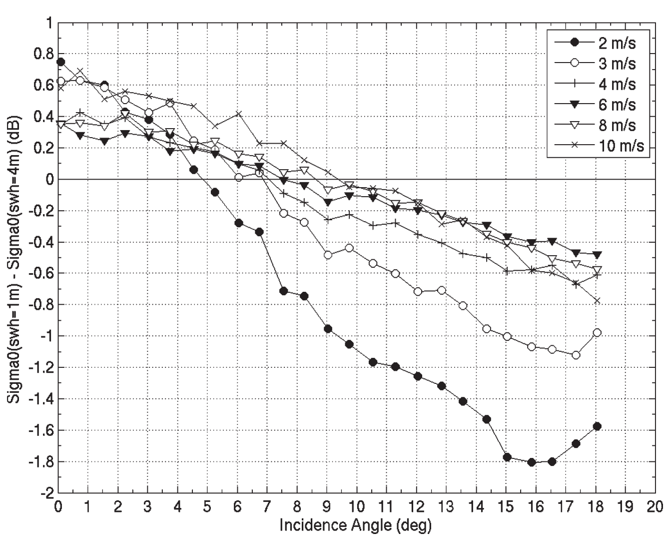

Fig. 4. Magnitude of the difference of σ_0 between low SWH (1 m) and high SWH (4 m) conditions as function of incidence angle for different wind speeds from light to moderate winds.

mixed seas including swell) δ exhibits the opposite trend. The overall picture shows that at a given wind speed, all curves (linear least-squares fits) associated to the different 1-m SWH classes intersect at a particular value of incidence angle θ_2 that shifts with respect to wind speed value.

Very similar results are obtained when reducing the crossover collocation criteria, i.e., with time within 1/2 h and 25 km in space (Fig. not shown).

The relative magnitude of σ_0 for extreme conditions, i.e., low and high SWH (1 and 4 m, respectively), is shown in Fig. 4 as a function of incidence angle for light-to-moderate wind speeds. For all wind speeds, we observe a positive magnitude at low incidence angles that decreases to reach a negative value at higher incidence. At 2-m/s wind, the magnitude is,

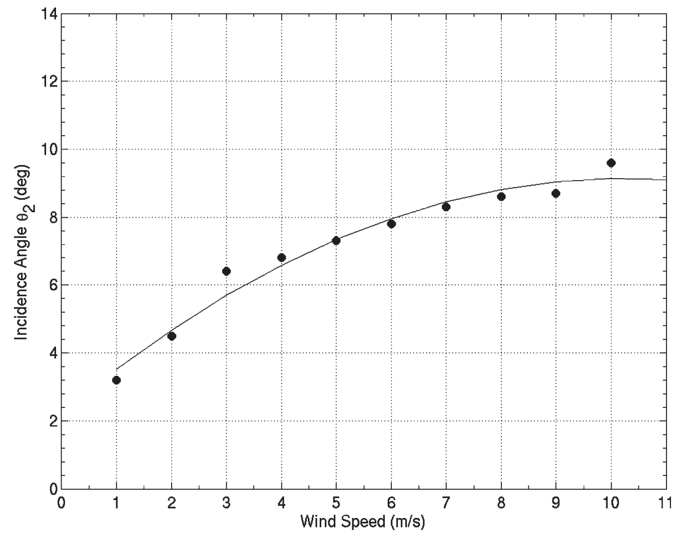

Fig. 5. Incidence angle θ_2 presenting a quasi-insensitivity of PR σ_0 to SWH at a given wind speed as function of wind speed. Overlaid is a quadratic regression fit to better display the trend.

respectively, ~0.8 dB at nadir and -1.6 dB at $\sim 18^\circ$. At 10 m/s, we observe almost similar absolute magnitude of variation (~0.8 dB) between the two extreme incidence angles. These results are consistent with previous analysis at higher incidence angles (20°, 30°, 40°, and 60°) [13]. However, in cases of moderate winds, these authors concluded that the existence of large waves with high SWH will not have significant impact on the radar backscatter since the observed differences were within the uncertainty of the radar (± 1 dB). The large amount of data available here helps to revise these conclusions. For these wind conditions, the presence of large waves significantly impact σ_0 from nadir to 18° except around a particular incidence angle, denoted θ_2 in Fig. 5, where σ_0 is insensitive to SWH at a given wind speed. As found, θ_1 and θ_2 angles are almost equal and correspond to the condition $\tan^2(\theta_1) = \tan^2(\theta_2) = \mathrm{mss}(U)$. Around these critical angles, the backscatter cross section is insensitive to significant wave height variations at a given wind speed.

One point of note for these TRMM PR data is that they represent horizontally polarized returns. There is a recognized difference in the response of horizontal and vertical polarization returns from the sea surface. The present results, in terms of overall features, can however be easily transposed to a vertically polarized result. Indeed, continuity between nadir viewing returns (no polarization) and scatterometer off-nadir returns in either one of the polarized states indicates that since sea state effects are observed in both polarizations when the backscatter is off nadir, all near-nadir measurements will display the same trends (in HH and VV). Previous analysis of the National Aeronautics and Space Administration Scatterometer (NSCAT) backscatter in each polarization state shows similar relative sea state impacts with respect to a global averaged backscatter that was derived by mixing all sea state conditions; they are slightly larger for NSCAT HH polarization measurement than on VV polarization data regardless of incidence angles between 16° and 50° [15], [19].

V. Conclusion

New approaches for viewing the global ocean using satellites have become available in the last decade. This letter focuses on sea surface roughness remote sensing and what can be learned using a multiple-satellite perspective with the specific goal being to provide new data to bridge the gap between what is known about nadir and off-nadir microwave scattering and emission from the ocean. Near-surface wind speed is a first-order geophysical parameter to be derived from microwave ocean sensors (the scatterometer, radiometer, and altimeter), but it is well known that the transfer function between their raw measurements and wind speed must account for perturbation due to surface wave processes that often deviate from simple local wind forcing behavior. Gaining quantitative insight on these sea state perturbations using field studies is notoriously difficult due to the inability to gather the sufficient range of surface conditions and data population.

This letter makes use of a multisatellite ocean observing opportunity, where a new type of ocean surface remote sensing data set, i.e., the TRMM cross-track scanning radar, is combined with coincident sea surface wave height information from crossing satellite altimeters to provide all-new data illustrating wave impacts on radar backscatter at multiple incidence angles. The resulting TRMM PR model function provides results showing that long-wave tilting effects are quantitatively confirmed in line with recent airborne slope measurements [20]. Accordingly, near-nadir cross-section measurements at a given fixed wind speed and ranging in incidence angles out to 20° are measurably related to the sea state dynamics. As a surrogate for the sea state's degree of development, the use of a collocated SWH parameter helps to document this impact and to clearly identify the off-nadir incidence angle that corresponds to the lowest fractional cross-section variation—a very useful angle to know in over-ocean radar calibration activities. Closer to scatterometer viewing angles (i.e., 16°–20°), our results show that for light-to-moderate wind conditions the presence of large waves can affect the performance of surface wind retrieval algorithms. Larger incidence angles are thus certainly to be recommended for surface wind scatterometry to minimize sea state impact. Near nadir, dual-frequency measurements and/or use of the contemporaneous SWH measurements will help to remove the longer wave contributions to leave the shorter ones [3]. At nadir and near-nadir configurations, dual-frequency capability will thus improve short surface wave observations and surface wind retrieval algorithm performances.

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