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To ensure aviation safety, air traffic safety agencies have required minimum aircraft separation standards. Currently, the FAA requires a minimum separation of 3 nautical miles (NM) when aircraft are within 40 NM of an air traffic control surveillance radar and a separation of 5 NM when aircraft are located beyond 40 NM from the radar. At the same time, the FAA permits a separation of 3 NM out to 60 NM for single sensor terminal systems using an ASR-9 Mode S MSSR. The ASR-9 Mode S and ASR-11 Monopulse Secondary Surveillance Radar (MSSR) are similar monopulse systems and the 40 NM limit on terminal separation minima for the ASR-11 may be unnecessarily restrictive. In this paper, we seek to determine if there are any differences in radar azimuth performance between the ASR-9 Mode S and the ASR-11 at ranges of 40 to 60 NM. To perform this analysis we implement a method that estimates radar error from raw time-stamped range and azimuth reports of aircraft flying through the airspace (targets of opportunity). The method filters the data to extract radar reports from aircraft traveling at nearly constant heading, velocity and altitude, and then utilizes knowledge of the aircraft dynamics to accurately estimate the true aircraft position. Our analysis employs a reference system approach comparing the performance of the alternative system, the ASR-11, against the performance of the approved legacy system, the ASR-9 Mode S, to determine if the alternative system's performance is equivalent or better.

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COMPARISON OF ASR-11 AND ASR-9 SURVEILLANCE RADAR AZIMUTH ERROR

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Abstract

To ensure aviation safety, air traffic safety agencies have required minimum aircraft separation standards. Currently, the FAA requires a minimum separation of 3 nautical miles (NM) when aircraft are within 40 NM of an air traffic control surveillance radar and a separation of 5 NM when aircraft are located beyond 40 NM from the radar. At the same time, the FAA permits a separation of 3 NM out to 60 NM for single sensor terminal systems using an ASR-9 Mode S MSSR. The ASR-9 Mode S and ASR-11 Monopulse Secondary Surveillance Radar (MSSR) are similar monopulse systems and the 40 NM limit on terminal separation minima for the ASR-11 may be unnecessarily restrictive. In this paper, we seek to determine if there are any differences in radar azimuth performance between the ASR-9 Mode S and the ASR-11 at ranges of 40 to 60 NM. To perform this analysis we implement a method that estimates radar error from raw time-stamped range and azimuth reports of aircraft flying through the airspace (targets of opportunity). The method filters the data to extract radar reports from aircraft traveling at nearly constant heading, velocity and altitude, and then utilizes knowledge of the aircraft dynamics to accurately estimate the true aircraft position. Our analysis employs a reference system approach comparing the performance of the alternative system, the ASR-11, against the performance of the approved legacy system, the ASR-9 Mode S, to determine if the alternative system's performance is equivalent or better.

Introduction

Current FAA regulation, Order JA 7110.65T 5-5-4 [1], states that when using an ASR-11 with Monopulse Secondary Surveillance Radar, aircraft must be separated by a minimum of 3 nautical miles (NM) when less than 40 NM from the radar antenna

and a minimum of 5 NM when 40 NM or more from the radar antenna. The same regulation extends the permitted use of 3 NM separation minima out to 60 NM for single sensor terminal systems using an ASR-9 with Mode S. The ASR-11 and the ASR-9 Mode S are similar monopulse systems, therefore the 40 NM limit on terminal separation minima for the ASR-11 may be unnecessarily restrictive. Consequently, the FAA Flight Systems Laboratory, AFS-450, commissioned a study to evaluate ASR-11 performance and determine if the ASR-11 can support 3 NM separation minima at ranges of greater than 40 NM. As part of this study, MIT Lincoln Laboratory was tasked with completing a large scale data analysis of ASR-11 performance. The results from this effort are presented in this paper. The AFS-450 study also includes three additional components which include evaluation of controlled flight test data, factory testing of the ASR-11, and an analytical comparison of the radar systems. The MIT Lincoln Laboratory effort will be considered in conjunction with these other components when determining the suitablility of the ASR-11 for extended 3 NM separation and does not on its own provide sufficient breadth to support a change in operational procedure.

The analysis evaluates the suitability of the ASR-11 for supporting 3 NM separation. A reference system approach is employed, comparing the performance of the alternative system, ASR-11, against the performance of the approved legacy system, the ASR-9 Mode S, to determine if the ASR-11 performance is equivalent or better. The radar errors are calculated using a technique developed in [2] to estimate radar azimuth error from large, widely distributed sets of radar data. Additional validation of the technique is performed to verify that is not dependent on range or elevation angle; two factors explored in this paper for their affect on radar azimuth error. Over 4 million error samples are collected from each radar type and analyzed. The error characteristics for each radar type

are then calculated and broken down by range, elevation and altitude for a comprehensive comparison of the systems. Finally, conclusions on the performance differences between the ASR-11 and ASR-9 Mode S are presented.

Background

Monopulse Secondary Surveillance Radar

The radar systems discussed in this paper consist of primary radar with co-located beacon interrogators, referred to as Monopulse Secondary Surveillance Radar (MSSR). Beacon interrogators are not technically radar but utlize radar-like technology [3]. Unlike primary radar, which detect targets from the reflected energy of a transmit pulse, beacon interrogators detect compliant aircraft by sending an interrogation signal to a transponder on board the aircraft and then processing the elicited response. Beacon systems are often referred to as "one-way" as they operate on transmissions travelling from the target to the radar antenna. This is in contrast to radar which rely on a "two-way" signal travelling from the radar to the target and then reflecting back to the radar. The monopulse in MSSR refers to the technique used to measure the azimuth of the target. Monopulse systems are more accurate and require fewer interrogations per aircraft than traditional "sliding window" systems, and consequently are the preferred and most widely used system in the National Airspace System (NAS) [4].

This analysis evaluates the performance of the beacon systems, and does not consider the performance of the primary radar. In this paper the terms ASR-11 and ASR-9 refer specifically and exclusively to the MSSR component of the radar system. Additionally in the case of the ASR-9, the term ASR-9 refers specifically and exclusively to an ASR-9 with a co-located Mode S.

Radar Azimuth Errors

Radar azimuth errors consist of a combination of two different errors: azimuth measurement error and radar azimuth bias. Azimuth measurement error is the error in the measurement of the aircraft's azimuthal position relative to the radar beam. Radar azimuth bias is a systematic error caused by a misalignment of the radar with true north. In the existing single sensor radar system, radar azimuth bias has minimal

effect on surveillance performance with respect to separation services. Single sensor radar systems apply a sensor's azimuth bias equally to all aircraft and the bias is in effect cancelled out in any separation measurements. All radar errors mentioned in this paper refer solely to the azimuth measurement error and do not account for any radar azimuth bias.

Azimuth Error Estimation Technique

The radar error estimation technique developed in [2] accurately estimates radar azimuth error using raw time-stamped range/azimuth radar reports from aircraft flying through the NAS, known as targets of opportunity (TOO), which provides a method for analyzing large quantities of radar data. The method filters TOO data so that it contains only aircraft flying straight and level at a near constant velocity, and then uses this a priori knowledge of the aircraft behavior to accurately estimate the true aircraft position and radar error.

The estimation technique involves a multi-step process. First, tracks of raw secondary reports from a single sensor recorded in radar coordinates (azimuth, slant range, and altitude) are projected onto a stereographic plane and stored in Cartesian coordinates (x, y) relative to the sensor. Each track is then passed through a filter that calculates the smoothed heading and velocity of the aircraft and extracts periods of straight and level flight at a near constant velocity. The straight and level tracks are then fed to the estimation algorithm. The algorithm estimates the true trajectory of the aircraft as the line that best fits the track in a least-squares sense. The algorithm estimates the true position of the aircraft at the time of each radar measurement by finding the set of points (x_i', y_i') on the least-squares line that minimize the summed distance between the points and the measurements (x_i, y_i), under the constraint of the aircraft flying at a constant ground speed v. More precisely, we are in search of the following set:

$$\{(x_i', y_i') \mid \min_{x_i', y_i'} \sum_{i=1}^{m} d_i, \frac{\sqrt{(x_{i+1}' - x_i')^2 + (y_{i+1}' - y_i')^2}}{t_{i+1}' - t_i'} = v\} \tag{1}$$

where d_i is the distance between the points (x_i, y_i) and (x_i', y_i'), and t_{i+1}' and t_i' are the time stamps of consecutive radar reports. The estimated true positions are then converted back into radar coordinates and the
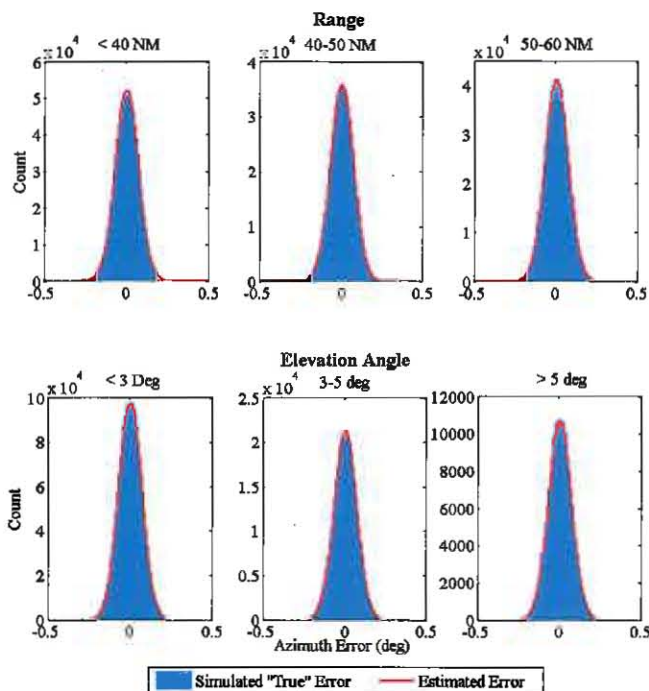
Figure 1. Estimation method validation

azimuth error is calculated for each measurement. A detailed explanation and validation of this estimation technique is found in [2].

Additional Estimation Method Validation

The analysis in this paper explores radar azimuth error dependence on range and elevation angle. To ensure the validity of the results, the estimation method accuracy must be shown to be independent of those factors. To supplement the general performance evaluation performed in [2], an analysis of the estimation method's accuracy relative to range and elevation angle was performed. The analysis generated 10,000 random aircraft tracks which were tracked by a simulated ASR-9 radar using the accepted error model for ASR-9 Mode S azimuth error, which consists of a zero mean normal distribution with a standard deviation of 0.068° [5]. The simulated radar reports were processed by the estimation method and the resulting azimuth errors are presented in Figure 1. The estimation accuracy is broken down by report range and elevation angle. The simulated ASR-9 error model [5] does not include any range or elevation angle dependent errors, so the simulated error, shown in blue, looks very similar across all the plots. In each sublot of Figure 1 the estimated azimuth er-

ror, illustrated as a red line, accurately captures the simulated true error, shown as a blue histogram. The estimation method performance shows no dependence on range or elevation angle and can therefore be used to estimate the azimuth error dependence on those same factors.

Analysis

Data Collection

Analysis was conducted on a collection of radar data supplied by the 84th Radar Evaluation Squadron (RADES). The data set consisted of 14 days of radar data from February 28th to March 13th, 2009. Radar reinforced beacon reports were collected from a total of 14 different radar; 7 ASR-9 and 7 ASR-11. The ASR-9 and ASR-11 sensors chosen for the analysis are listed in Tables I and II respectively.

The radar reports consisted of range, azimuth and pressure altitude measurements. Prior to projection onto a stereographic plane the pressure altitude measurements were corrected using local weather data. Aircraft altitude is reported as Mode C pressure altitude from sea level on an average day, barometric pressure of 29.92 mm Hg. As local barometric pressure deviates from this standard, Mode C altitude reports become inaccurate. To ensure accurate position projections the Mode C altitude reports were corrected to the true altitude using the local hourly barometric pressure and temperature from online sources [6]. Each altitude corrected radar report was then projected onto a stereographic plane tangential to its sensor and stored in a database in both radar and Cartesian coordinates. The local weather data required for Mode C altitude correction was incomplete on some days. Therefore data from these periods were not included in the analysis. Using the estimation technique in [2], radar azimuth errors were calculated for all reports from ASR-11 sensors and for all monopulse reports from ASR-9 sensors. A total of 8,588,036 radar reports were analyzed; 4,334,946 from ASR-9 sensors and 4,253,090 from ASR-11 sensors.

1. Results

Azimuth Error Comparison

Figures 2 through 4 show the estimated azimuth error distributions for the ASR-9 and ASR-11 surveillance radars. Figure 2 shows the results for the full
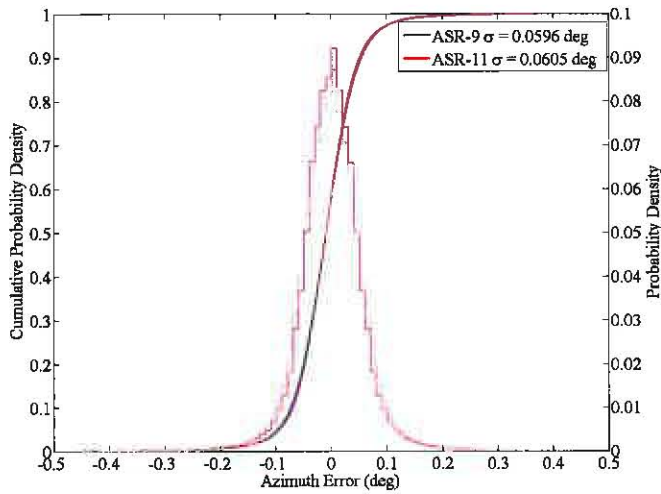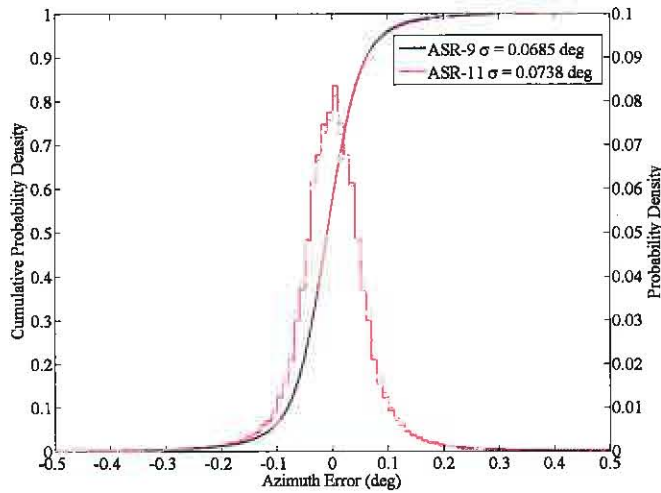
Figure 2. Overall azimuth error
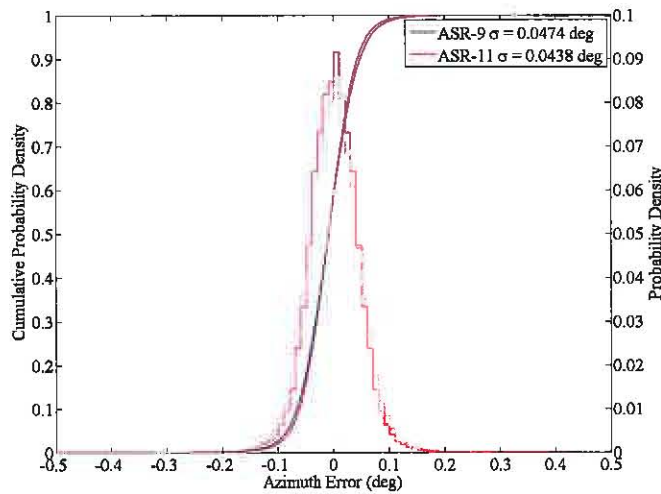

Figure 3. Azimuth error for ranges <40 NM

Figure 4. Azimuth error for ranges 40-60 NM

Table I. ASR-9 Sensors

Site Location	Site ID
Baltimore, MD	BWI
Chicago, IL	ORD
Boston, MA	BOS
Los Angeles, CA	LAX
Manchester, NH	MHT
New York, NY	JFK
Newark, NJ	EWR

Table II. ASR-11 Sensors

Site Location	Site ID
Colorado Springs, CO	COS
Columbia, MO	COU
Lafayette, LA	LFT
Saginaw, MI	MBS
Stockton, CA	SCK
Waco, TX	ACT
West Palm Beach, CA	PBI

data set. Figure 3 shows the azimuth errors for the subset of reports 40 NM or less from the radar antenna, the ranges where 3 NM separation minima is permitted for the ASR-11. Figure 4 shows the azimuth error for the subset of reports 40 NM to 60 NM from the radar antenna, the extended range at which 3 NM separation minima is permitted for the ASR-9 but not for the ASR-11. Each plot contains a cumulative distribution function (CDF) and probability density function (PDF) of the errors for both the ASR-9 and the ASR-11. The ASR-9 error PDF is represented by the light-blue histogram and the ASR-11 PDF is represented by the red outlined histogram. The ASR-9 error CDF is plotted as a blue line and the ASR-11 error CDF is plotted as a red line. The right y-axis refers to PDF density values, while the left y-axis refers to the CDF density values. The statistical standard deviations of the ASR-9 and ASR-11 distributions are recorded in the plot legend.

Figure 5 plots the estimated azimuth error as a function of range and altitude. The top plot contains the ASR-9 results, while the bottom plot contains results for the ASR-11. The x-axis represents the range of the targets and the y-axis the altitude of the targets. Dotted lines representing elevation angles are drawn on the plot for reference. The plots are broken down into cells 0.5 NM in range by 2,000 feet in altitude. Each cell is assigned a color corresponding to the
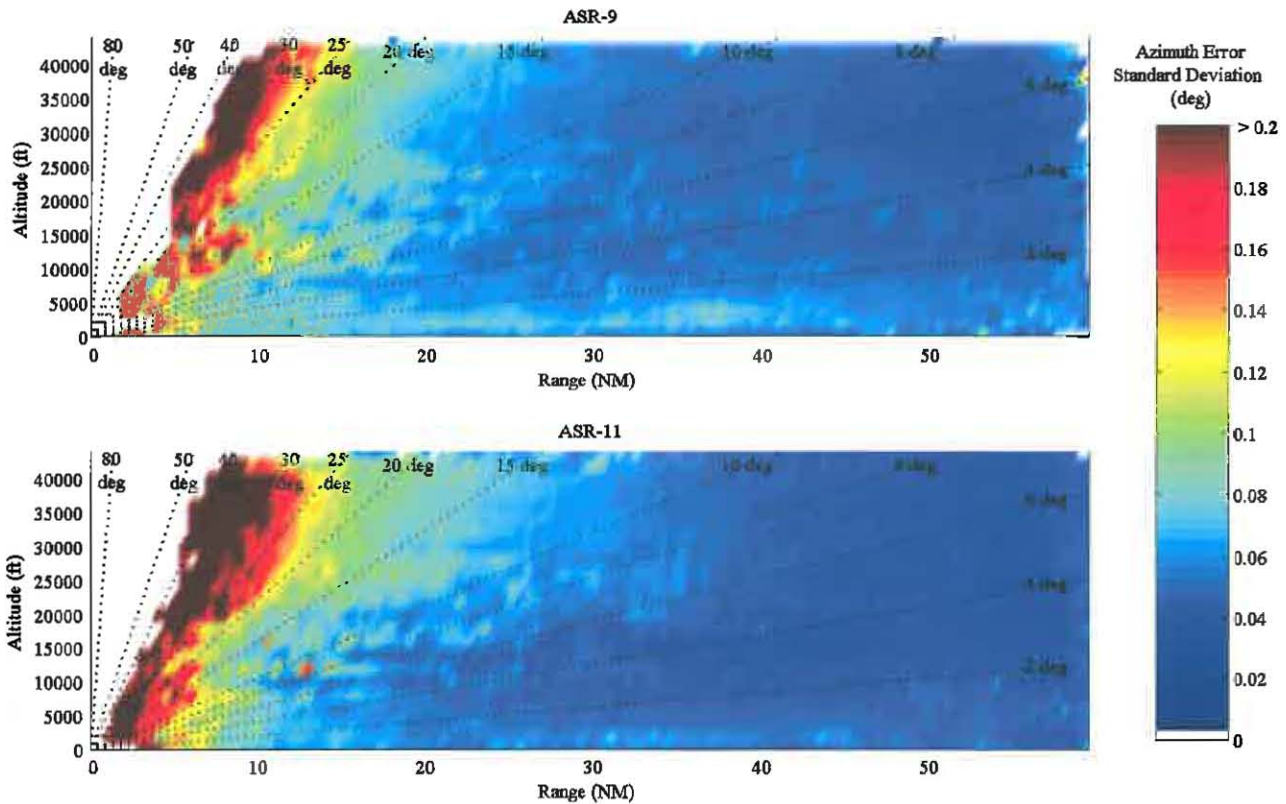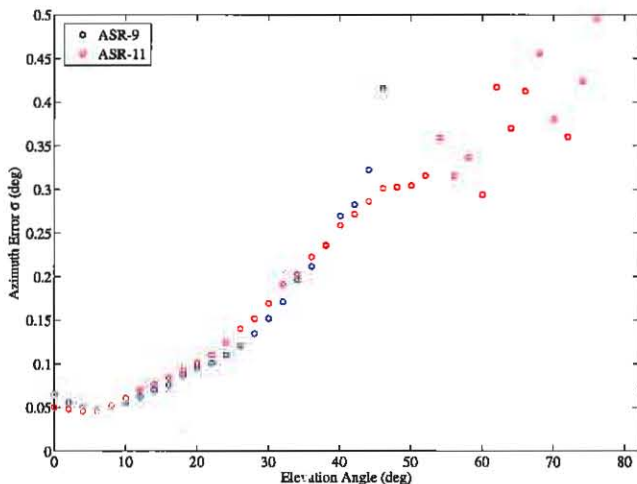
Figure 5. Azimuth error vs. range and altitude

Figure 6. Azimuth error vs. elevation angle

cells are then interpolated to a finer resolution for a smoother image. The azimuth error value for each color is shown in the colorbar to the right of the plots. White-space represents areas where no target reports were recorded. Figure 6 plots the estimated azimuth error standard deviation versus elevation angle for each sensor type.

Figures 3 and 4 illustrate that the estimated azimuth error characteristics for the ASR-11 are nearly identical to those for the ASR-9. Most notably, ASR-11 azimuth errors for reports at ranges of 40 to 60 NM appear to be equivalent to the azimuth errors for the ASR-9 at the same ranges. This conclusion is reinforced in Figure 5, where the right halves of the ASR-9 and ASR-11 plots display the same error levels.

Figures 5 and 6 show azimuth error increases rapidly with elevation angle for both sensor types. This behavior is not unexpected as the accuracy of monopulse systems degrades at higher elevation angles [4]. The results are encouraging from an analysis perspective, as they demonstrate that the

magnitude of the standard deviation of the azimuth error of the reports in the cell. The colormap ranges from dark blue, representing small azimuth errors, to red, representing large azimuth errors (standard deviation of greater than 0.2 degrees). The colored

analysis method captures an expected degradation in performance.

The results show that for reports within 60 NM of the radar, elevation angle is the dominant factor in radar azimuth accuracy, while range and altitude have relatively little effect. Figure 3 shows both sensors having larger azimuth errors at short ranges compared to long ranges (Figure 4), but this behavior is expected due to the azimuth error dependence on elevation angle. Aircraft flying at the same altitudes will be at higher elevation angles relative to the sensors at short ranges than at long ranges, so subsequently the azimuth errors will be larger at short ranges.

Figures 3 and 4 show that for the data set analyzed, the ASR-11 surveillance radar is capable of occasionally receiving reports at higher elevation angles than the ASR-9 surveillance radar. However, the number of reports received at high elevation angles (> 45 deg) by the ASR-11 was relatively small; roughly 3,500 out of 4,000,000 reports, and had minimal effect on the final results.

Conclusion

The performance of the ASR-9 and ASR-11 surveillance radar were compared using a large collection of estimated radar errors. The results found that the azimuth error of ASR-11 surveillance radar ($\sigma = 0.0605$ deg) was similar to that of ASR-9 radar ($\sigma = 0.0596$ deg). In particular, for targets in the region of interest, 40 to 60 NM from the radar antenna, the ASR-11 azimuth error ($\sigma = 0.0438$ deg) was equivalent to the ASR-9 azimuth error in the same region ($\sigma = 0.0474$ deg). The results of this analysis support the supposition that the 40 NM limit on 3 NM separation minima for ASR-11 surveillance radar may be unnecessarily restrictive.

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