SYSTEMS ENGINEERING OF LOW COST AESAS FOR HIGH VOLUME CONSUMER LEO SATELLITE GROUND STATIONS

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***Abstract*—Active Electronically Scanned Arrays (AESAs) are used in radar and communication systems for both military and commercial applications. Extensive effort has been invested in the development of AESAs over the last 25 years. This is especially true for some of the key subsystems such as the T/R module and components such high power amplifiers. However, a new set of opportunities for phased arrays is requiring a fresh look at how AESAs are developed, fabricated, integrated, deployed, and maintained. This has promoted the need for a systems engineering investigation into their development. This work focuses on the systems engineering up to the concept development stage of an ultra low cost AESA. An extensive customer needs analysis is performed along with trade studies and baseline description. The T/R modules, antenna, and key integrated circuits are discussed. The target market is high volume consumer grade ground stations for Low Earth Orbital (LOE) satellite communication—Consumer LEO Ground Station (Consumer LEO-GS). The analysis is specific to Ku-Band systems, but much of what is presented can be applied to other bands such as Ka-Band.**

Keywords—phased array; AESA; radar; communication; LEO satellite.

Section 1: Introduction

Phased arrays use transmit/receive (T/R) modules to achieve the electrical functions required for antenna beam steering. They also contain the high power amplifiers for transmit signals, and low noise amplifiers for the receive signals. Phased arrays using T/R modules have been used or proposed for use in:

- Military radar systems such as the AN/APG-79 radar used in airborne systems [1].
- Communication systems for data transfer with unmanned aerial vehicles (UAVs) [2].
- Deep-space communication systems [3].
- Ground stations for communication between submarines and satellites [4].
- Wi-Fi communication systems to overcome multipath and crowded spectrum issues [5].
- SatCom on the move systems with the Tx and Rx functions performed in separate modules [6].

More recently, AESA phased arrays have been proposed as a solution for Low Earth Orbital (LEO) satellite systems. This represents a significant and emerging opportunity due to the number of ground stations that will be required. Other areas of research for phased arrays are 5G networks and internet of things (IoT) systems [7]. However, these new phased arrays will need to use innovative T/R module technologies, integrated circuits, and planar antenna elements with feature sets required to achieve the cost, performance, manufacturability, and reliability necessary.

As a result the complete life cycle of the AESA must be reexamined for these high volume commercial (non-military) and consumer systems. Customer requirements and functions must be examined so that proper technology choices result. To this end, five elements of systems engineering of an AESA are presented that are particularly important in order to support the new opportunities that have emerged.

Customer needs are discussed in Section 2. A customer survey is performed as an objective means to understand customer needs. The System and Context Description is explored in Section 3. The AESAs used in LEO systems have a context that is different than traditional AESAs. This context must be clearly described and understood prior to development of baseline concept. The system functional description is described in Section 4. Some of the major functions of the AESA used in these new systems are common with prior systems. However, the differences are significant enough and for a complete treatment a description of the more unique features is presented. Trade Studies are covered in Section 5. Results of two trade studies are presented and one of them is shown and described in detail. They are the configuration of the T/R module and the choice of semiconductor material for the front end electronics. The engineering trade studies provide data that is used during the detailed engineering development phase. The Baseline Solution Description is shown in Section 6. Based on the customer needs, required context interactions, and trade studies, a baseline solution is described mainly in terms of functions. For several key functions, specific solutions are discussed and major components are defined. The paper concludes in Section 7 with a summary and suggestions for further study.

Section 2: Customer Needs Analysis

The primary end customer for the proposed system is consumers. A customer needs analysis is required to confirm the expectations of the customer so that a feasible solution can be developed. The three top customer needs are reported, an initial analysis of them, and results of an internet survey of potential customers.

The analysis of customer needs focuses at the consumer level. The top three customer needs are: cost of the hardware, size of the antenna, and performance of the system. The initial needs analysis is performed from the perspective of the end user. The initial needs analysis results are summarized as:

1. Cost: Consumers are used to a particular price point for the hardware (satellite dish, low noise block (LNB), and set top box) portion of a satellite TV service. This sets a cost expectation for the consumer for any type of satellite connectivity. Based on this, the satellite TV market hardware cost was chosen as a guide for what consumers are willing to pay for the hardware portion of an AESA LEO ground station.
2. Antenna Size: Consumers expect small antennas for their satellite connectivity. This is because the antennas are mounted on the tops of homes, apartment balconies, and other visible locations. It is anticipated that customers will need a solution that is similar to their prior experience with satellite antennas. Like it or not, satellite TV systems have set an expectation with consumers on antenna size. This means that the size of the AESA LEO ground terminal will need to be similar to the 0.6 m^2 of satellite TV systems.
3. Availability of The System: The system must perform in weather conditions such as rain fade and snow. Customers expect a reliable system with very high levels of availability (i.e., maintain data rate).

While this initial analysis was useful and provided insights into customer needs, a more objective analysis was required. Therefore, an internet survey was performed using a third party internet survey company [8]. Five questions were generated to either confirm or modify the initial needs analysis. Following suggestions in [9] the questions were configured to allow customers rank levels of importance for the three needs being reported. The survey was administered to a sample size of 250 persons [10, 11, 12]. The sample size was calculated using

$$n = \frac{z^2 p(1-p) \big/ e^2}{1 + \left(z^2 p(1-p) \big/ e^2 N \right)} \tag{1}$$

Where:
n = sample size
N = population size

e = margin of error
p = expected proportion (prevalence) which is estimated at 50%.
Z = Z statistic based on level of confidence desired (i.e., for 95% confidence, Z = 1.96).

For a potential customer base of 5 million users (n = 5,000,000), 95% confidence (Z = 1.96), and a margin of error of 6%, calculations using (1) give the required sample size as 267. Since a sample size increment of 250 falls within a pricing block of the survey company hired for administering the survey, a sample size of 250 was chosen. This increases the margin of error to 6.2% which is acceptable for this investigation. Additional statistically important information was gathered regarding the survey respondents such as income levels, age, and gender. 43.57% of respondents had a household income of less than $49.99K, and 19.5% were $50-74.99K. The age population distribution was distributed in four brackets of 18-29 years old (24.52%), 30-44 years old (23.75%), 45-59 years old (24.52%), over 60 years old (27.02%). As far as gender, 52.1% were female, and 47.89% were male.

The survey questions address the three needs of cost, size, and availability. However, the initial needs analysis focused on the cost of the system hardware while the survey questions also include the monthly service cost. This additional parameter was added to provide additional insight into the cost sensitivities of the customer. The questions are:

1. In order for you to be interested in buying a satellite internet system, what size must the outside antenna be?
    a. The same size as a typical satellite TV antenna,
    b. Smaller than a typical satellite TV antenna,
    c. It can be as large as twice the size of a satellite TV antenna.
2. Assuming the per month service price is attractive, what is the maximum price you willing to pay for the equipment?
    a. Less than $75,
    b. Between $75 to $150,
    c. Between $150 to $250.
3. How many times per year can the service be unavailable due to weather (rain/snow) before you will consider cancelling your service?
    a. Once is too much,
    b. 1 to 3 times,
    c. 3 to 5 times,
    d. 5 to 10 times.
4. Which is more important to you?
    a. Installation price.
    b. Monthly service price,
    c. The size of the antenna that is mounted outside on your house or apartment.
5. Rank the four items below on level of importance
    a. Installation price,
    b. Monthly service price,
    c. The size of the antenna,
    d. Performance of the system during rain/snow.

The responses to question 1 are shown in Figure 1. Note that approximately 93% of the respondents said that they expect the antenna to be the same size or smaller than existing satellite TV antennas. This should come as no surprise and agrees well with the customer expectation of solutions with an antenna area of approximately 0.6m or less.

It should also come as no surprise that approximately 70% of respondents to question 2 expected the cost of equipment to be less than $75.

A bit unexpected is that approximately 45% of respondents to question 3 were willing to have the service unavailable due to weather conditions 1 to 3 times per year before considering the cancellation of the service.

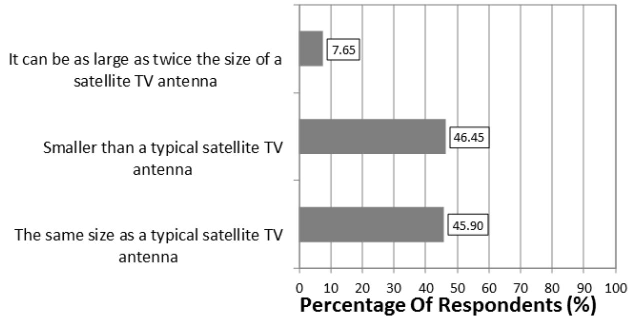


Figure 1. Summary of responses to Question 1.

On question 4, the vast majority of respondents, approximately 94%, rank the monthly service charge as more important than installation price and the size of the antenna. The size of the antenna was ranked as more important by only about 2% of respondents.

Question 5 is nearly the same as question 4. However, there is an important difference and the results of the survey illustrate the difference. Since question 5 asks the respondents to rank the importance of the four options, this question provides insight into the relative rank between the four alternatives. The interesting result here is that installation price and availability of the system were ranked the second most important concerns by over 75% of respondents (35.85% and 39.94% respectfully). As expected from question 4, fully 74% of respondents ranked monthly service charge as most important. Interestingly, 72% of respondents ranked the size of the antenna as the fourth most important concern.

Based on these results, the initial customer needs analysis was essentially confirmed except that monthly service cost was added to the cost parameter. In addition, cost and availability are now ranked as more important customer needs than size of the antenna.

Section 3: System and Context Description

A LEO satellite system differs from the more familiar geostationary (GEO) satellite. For the GEO systems, the satellite is stationary relative to the surface and rotation of the earth. This is an important advantage since it allows ground stations to use antennas that are fixed and do not move. For instance, this is the case for satellite TV dishes. The dish is installed and permanently points to the same position in the sky.

For LEO satellites, the situation is very different. LEO satellites move relative to a position on the earth. This means that for an observer on the surface of the earth, the LEO satellite will move from one horizon and across the sky to the other horizon. From the perspective of the consumer ground terminal, the most important difference between the GEO satellite and LEO satellite system is antenna must scan to maintain connection with the satellite. In other words, the antenna beam must point to satellite as it moves across the sky. This can be accomplished mechanically so that the antenna rotates using electric motors or other means. Alternatively, the antenna beam can scan electronically. Electronic scanning can be achieved using an AESA which can keep the antenna beam ‘locked’ on the satellite as it moves across the sky. The AESA can also switch rapidly to a different satellite as the current satellite moves out of range.

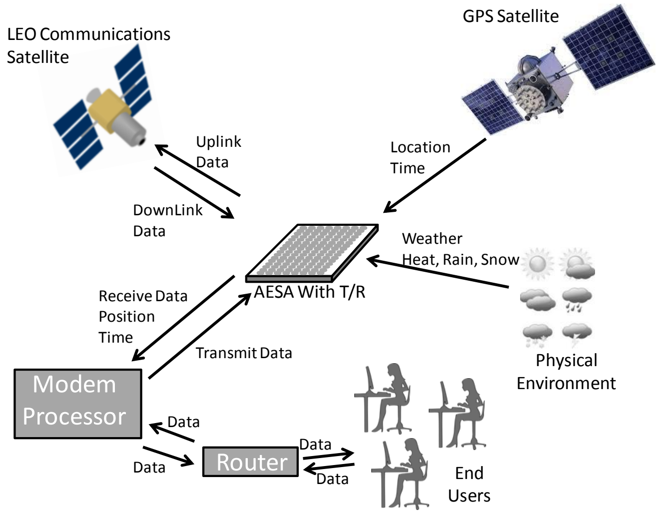


Figure 2. Context diagram showing how the AESA interacts with the external elements.

Mechanically scanned systems suffer from limitations of cost, reliability, manufacturability, size, and slew rate. Slew rate is the time it takes the antenna to move across its field of view (FOV). For these reasons, this work considers only AESA solutions and focuses on the systems engineering concept development of the T/R modules used in these systems.

The context diagram is shown in Figure 2. Note how It shows the LEO communications satellite in a up/down link to the AESA with time and location information being received from the GPS satellite. Another important factor is the environment with weather such as rain. The user is connected to the AESA through the modem/processor and router. Data is passed from the end users up to the AESA to complete the up/down link to the LEO communications satellite.

Section 4: System Requirements

A set of functional requirements is developed. This is not a detailed performance specification, since it comes later in the development. Rather, it is a description of what the system should do—“tasks or activities that the system performs during its operation” [13]. Although most AESAs adhere to a fairly common set of functions, this analysis reveals the functions that are unique to Consumer LEO-GS systems. Also, the functional requirements cover the AESA and the complete ground terminal. The top 8 functional requirements are:

- The system should automatically determine its position, orientation, and time of day so that the pointing algorithm will know where to point the AESA for connection to the LEO satellite.
- The complete system should be less than $100 to the consumer with a goal of less than $75.
- The system should be capable of at least 20MBPS data down link connectivity.
- The AESA shall provide the receive G/T performance and transmit EIRP to maintain connectivity in the presence of rain fade with degraded data rate allowed.
- The AESA shall have a sufficient scan range without grading lobes for always having at least one satellite in the field of view (FOV) capable of supporting the required data bandwidth.
- The system must maintain high availability. The required availability can be calculated by letting T_{NA} equal the number of days the system is not available which the consumer survey gave as 3 days and T_A equal the number of days in the year the system is available which is 365 - T_{NA} = 362. The availability is then given by

$$A_0 = \frac{T_A}{T_A - T_{NA}} = \frac{362}{362+3} = 99.18\% \qquad (2)$$

- The AESA antenna shall not be larger than 0.6m^2. This requirement is at odds with the G/T and EIRP requirement.
- The AESA must operate over the environmental temperature range of -40 to +60 C and survive 100% humidity.

These functional requirements capture the main functional requirements for the system.

Section V: Trade Studies

The trade studies provide data and decision traceability for the engineering development activity of the product life cycle. The results of two trade studies are given in this section. Because of size constraints only one of the trade study table is included in this report.

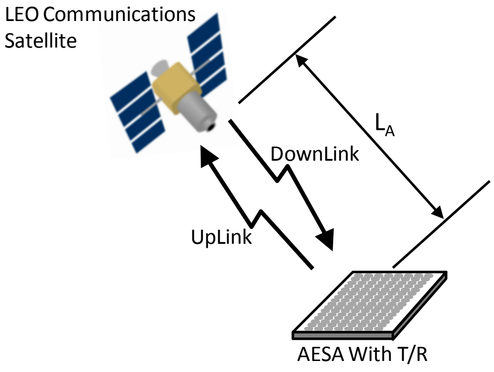


Figure 3. Uplink and Downlink that exist between the AESA and the satellite.

The first trade study is on the possible configurations for realizing the T/R modules. This study is important since prior generations of T/R modules will not meet the size or cost constraints of consumer LEO ground stations [14]. The trade study considers eight possible configurations which includes the variations on the T/R module electronic packaging and materials. The result shows that the T/R module must be integrated as part of the antenna itself to meet the size, cost, and performance. The impact of T/R module configuration on cost and size is obvious. The performance impacts of T/R module configuration are less obvious. The communications link budget depends upon key electrical performance such as receive noise figure and transmit power. Those parameters are directly impacted by the T/R module configuration.

One of the key parameters for the T/R configuration as it relates to the overall system is the link budget between the ground station and the satellite. Figure 3 illustrates the link.

The key parameters in the link are the power of the transmit signal (P_T), the gain of the transmit antenna (G_T), the noise temperature of the receiver (T_{SYS}), the gain of the receive antenna (G_R), the frequency of operation, and the slant distance between the satellite and ground antenna (L_A). With this information it is possible to calculate the signal to noise ratio at either the satellite or the receiver using

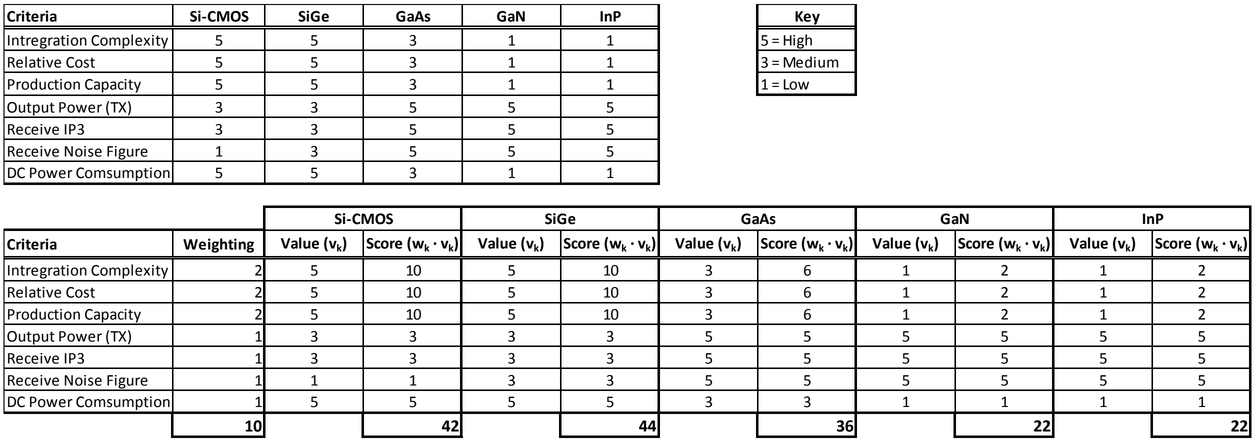
$$\frac{S}{N} = P_T G_T \left(\frac{\lambda}{4\pi R}\right)^2 L_A \frac{1}{kB} \frac{G_R}{T_{SYS}} \qquad (3)$$

Where λ = wavelength of operation, k = Boltzmann's constant = 1.38 x 10^{-23} m^2kg/s^2K, B = data bandwidth (Hz). This equation can be used to find the signal to noise ratio at either the satellite (for the uplink) or the AESA ground station (on the downlink). It is very common for the parameter E_b/N_0 to be used instead of S/N, but they are related by

$$\frac{E_b}{N_0} = \frac{S}{N}\frac{B}{R} \qquad (4)$$

Where R = digital data rate. This give the ratio of the energy per bit transmitted to the power spectral density of the noise.

The second trade study is on the integrated circuit technology options. The analysis includes integration complexity, relative cost, production capacity, output power (transmit), receiver third order intercept (IP3), receiver noise figure, and DC power consumption. The trade study considers silicon CMOS (Si-CMOS), silicon germanium (SiGe), gallium arsenide (GaAs), gallium nitride (GaN), and indium phosphide (InP) semiconductors. The result shows that the semiconductor material of choice is SiGe since it offers key performance parameter performance needed such as noise figure and output power at a cost that meets system needs. One may argue that the ranking of 3 for the noise figure of SiGe and 5 for GaAs is not correct since SiGe noise figure is approaching GaAs. While this is true, GaAs still achieves lower noise figure which is a major determining factor in system G/T. More important, if the ranking of SiGe is increased to be equal to GaAs, the result of SiGe as the solution will still be achieved but with even greater margin since SiGe rank would increase from 44 to 46 and all others would remain the same. So such an objection will would not affect the result. Another observation is that Si-CMOS is a close second to SiGe. While this is true, it has lower noise figure than SiGe which, as already stated, is an important system performance parameter. Therefore, SiGe is selected as the material of choice.



Criteria	Si-CMOS	SiGe	GaAs	GaN	InP
Intregration Complexity	5	5	3	1	1
Relative Cost	5	5	3	1	1
Production Capacity	5	5	3	1	1
Output Power (TX)	3	3	5	5	5
Receive IP3	3	3	5	5	5
Receive Noise Figure	1	3	5	5	5
DC Power Comsumption	5	5	3	1	1

Key
5 = High
3 = Medium
1 = Low

		Si-CMOS		SiGe		GaAs		GaN		InP	
Criteria	Weighting	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)	Value (v_k)	Score ($w_k \cdot v_k$)
Intregration Complexity	2	5	10	5	10	3	6	1	2	1	2
Relative Cost	2	5	10	5	10	3	6	1	2	1	2
Production Capacity	2	5	10	5	10	3	6	1	2	1	2
Output Power (TX)	1	3	3	3	3	5	5	5	5	5	5
Receive IP3	1	3	3	3	3	5	5	5	5	5	5
Receive Noise Figure	1	1	1	3	3	5	5	5	5	5	5
DC Power Comsumption	1	5	5	5	5	3	3	1	1	1	1
	10		42		44		36		22		22

Figure 4. Trade study results for selecting the semiconductor technology.

As part of the trade study analysis, the total cost of the SiGe die used to populate the phased array was analyzed. The analysis used a fixed die size of 4mm x 4mm, an array size of 18” x 18”, with 20 x 20 elements. One of the results of the analysis is shown in Figure 5. It shows the total cost of die used in the array as a function of number of T/R channels per die and the cost of fabrication of the SiGe wafer. In other words, each SiGe IC can have multiple T/R channels. Note the total cost of SiGe die drops below $30 for the case of 5 channels per die at a cost of $1250 per wafer. This analysis assumes a 12 inch waver and a die yield of 85%. Note that for every million consumer ground stations produced, approximately 10,000 wafers will be required.

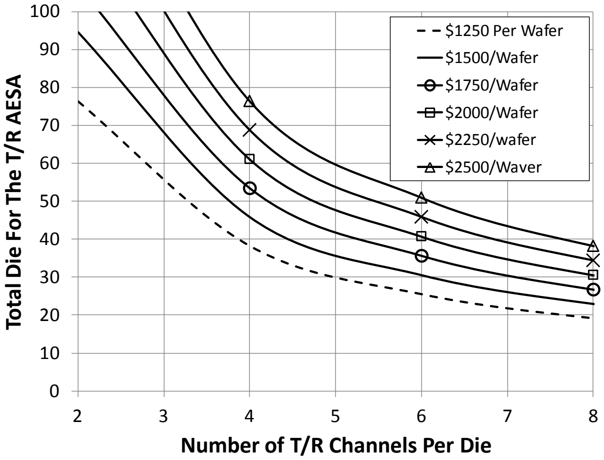


Figure 5. Total cost of die for the AESA as a function of the number of T/R channels per die.

If the current customer base of satellite TV suppliers is an indication of the available market for these systems, then these types of systems will require trillion wafers. The current number of worldwide satellite TV subscribers is approximately 950 million [15]. If this is multiplied by the 10,000 wafers per 1 million consumer ground stations, then the result is a need for 9.5 trillion SiGe wafers to support this market.

The size of the array in these trade studies is approximately 0.2 square meters which is well below the goal of 0.6 square meters.

Section 6: Baseline Solution Description

A baseline is chosen and described. The baseline design for the AESA is described in terms of the T/R module configuration, integrated circuits, and the antenna system.

T/R Module and Integrated Circuits: The T/R module is realized using SiGe integrated circuit technology. This choice is based on the required noise figure, output power, and cost. Alternatives such as GaAs and GaN are too costly to be viable alternatives. Si-CMOS does support the cost objectives, but it does not simultaneously support the noise figure requirements and receive linearity requirement (at least at this point in time).

The antenna system is planar and proposed to be fabricated using low cost laminate circuit board material.

Section 7: Conclusions and Future Work

This work presents the concept development stages of an AESA based ground station for LEO satellite communication. Much more systems engineering is required before the detailed work can begin. In fact, a complete analysis on the feasibility of the baseline solution should be one of the next steps in this investigation.

Several of the important systems engineering activities are presented and results for the AESAs intended for Consumer LEO-GS systems. The Customer Needs analysis revealed a few surprising results from the customer survey. Namely, the number one concern among customers is the monthly service cost and the size of the antenna ranked behind monthly cost, hardware cost, and availability. However, the survey also revealed that the existing satellite TV systems are setting many of the expectations on cost, size, and availability. The Functional Specifications outlined the major functions that the T/R modules must perform and how the functions are tied the customer needs. The Trade Study analysis focused on the two items that drive measures of effectiveness (MOEs) and in particular cost. The baseline solution is then discussed as a feasible solution that meets the customer needs.

The analysis showed that for every 1 million Consumer LEO-GS produced, there will need to be approximately 10,000 SiGe wafers produced. The analysis revealed what may be the most significant result of this analysis which is that the addressable market for SiGe wafers for this type of system is 9.5 trillion wafers. If this line of thinking is correct, then this raises important questions about the world wide fabrication capacity in SiGe to meet this demand.

Moreover, some specific systems engineering work that should be conducted includes the up/down link, the LEO satellite, the AESA, and the rest of the ground station such as the processor and array controller. A formal risk assessment and mitigation plan is also required.

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