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MONOPULSE SECONDARY SURVEILLANCE RADAR ANTENNA FOR AIR TRAFFIC CONTROL

Pavel Bezoušek[1], Vladimír Schejbal[2]

Summary: Secondary Surveillance Radar (SSR) play an important role in the Air Traffic Control of civilian and military aircrafts. It is frequently integrated with primary radars having antennas of both radars mounted on a common mast. Such an arrangement brings serious constrains on antenna size and weight. The design of a SSR antenna, for such an integrated arrangement is presented in the paper and solutions of the related problems are described.

Key words: Air Traffic Control, Monopulse Secondary Surveillance Radar (MSSR), Primary Radar, Interrogation Sidelobe Suppression (SLS).

INTRODUCTION

For civilian applications, the Secondary Surveillance Radar (SSR) is used for Air Traffic Control together with the Primary Surveillance Radar. SSR works by triggering a transponder in the aircraft, which generates its own coded return signal, so that the SSR signal requires much less power than the primary radar one (1), (2), (3). The coded return signal contains information on the identity and height of the aircraft and can possibly give emergency and further information on aircraft.

The antenna system of a modern SSR creates usually three beams: the sum, the difference and the SLS ones. The sum beam serves for transmitting the interrogation signal and for receiving the transponders replies (targets) detection. To prevent the transponder being triggered by any other signal at the same frequency the transmitted signal is specifically coded. However, the sum beam sidelobes may also cause replies from aircraft, which are close to the radar. Therefore Interrogation Sidelobe Suppression (ISLS) is used to prevent the same aircraft appearing on several bearings simultaneously via sidelobes. Control pulses transmitted by the SLS beam which pattern is omnidirectional with a null in the direction of the sum mainlobe. Hence the control pulse magnitude in space is less than those of the interrogation ones within sum mainlobe but it is of a greater magnitude in the sidelobe region. The transponder will respond only when the interrogation pulses are greater of the control pulse by 6 dB or more. Similarly the SLS beam is used for rejection of false received signals through the mainbeam sidelobes (RSLS). The required SLS beam pattern is achieved by driving the central element (backfill antenna) with half the input power of which a small proportion is fed to the remaining elements in antiphase with the central element.

[1] prof. Ing. Pavel Bezoušek, CSc., University of Pardubice, Faculty of Electrical Enineering and Informatics, Department of Electrical Engineering, Studentska 59, 532 10 Pardubice, Czech Republic, Tel.: +420 466 036 035, E-mail: pavel.bezousek@upce.cz
[2] prof. Ing. Vladimir Schejbal, CSc., University of Pardubice, Jan Perner Faculty of Transport, Department of Electrical Engineering, Electronics and Signalling in Transport, Studentska 59, 532 10 Pardubice, Czech Republic, Tel.: +420 466 036 293, E-mail: vladimir.schejbal@upce.cz

An accurate aircraft bearing measurement is ensured by using Sum/Difference Monopulse. The replies from the aircraft are received simultaneously via a sum and a difference patterns. The difference pattern has a sharp null at the center of the sum mainlobe. By exploiting the ratio of the difference and the sum beams the azimuth bearing can be found accurately even in the case of receiving only one or a few replies.

The most direct way of correlating primary and secondary data is to mount both antennas on one rotating shaft. To prevent excessive weight and wind loads on turning gear, the SSR antenna should be made as small and light as possible. For many years the standard configuration for interrogators consisted of a linear array (commonly called a hog trough because it resembles an animal feeder) and a stationary omnidirectional antenna. Today, to reduce signals reflected from the ground and surrounding objects, which can give rise to further interrogations and false plots at different azimuth angles, a Larger Vertical Aperture (LVA) is used. LVA with a shaped aperture distribution can give a vertical radiation pattern allowing balance between reducing ground reflections and providing sufficient low angle coverage.

The paper describes an attempt to integrate antennas into one antenna unit for primary and secondary radars.

1. SSR ANTENNA

The SSR antenna with a shaped aperture distribution is a planar array with operating frequencies of 1,03 and 1,09 GHz. Suppose that antennas of an array are located at points $\mathbf{r_1}$, $\mathbf{r_2}$, and so on. We obtain the total pattern of the antenna array by adding the electric fields radiated from any antenna. If the individual antennas (elements) have identical element patterns, we can separate the pattern into a product of an element pattern and an array factor F (3), (4), (5), (6). Then the array factor is given by the following equation

$$F = \sum_{m=-M}^{M} \sum_{n=-N}^{N} I_{mn} e^{jk(md_x T_x + nd_y T_y) + j\psi_{mn}} \qquad (1)$$

where the coordinate system is considered according to Fig. 1, I_{mn} are amplitudes, ψ_{mn} are phases, $k = 2\pi/\lambda$, λ is a wavelength, d_x and d_y are the element spacing along x and y axes, $T_x = \sin\Theta \cos\Omega$ and $T_y = \sin\Omega$.

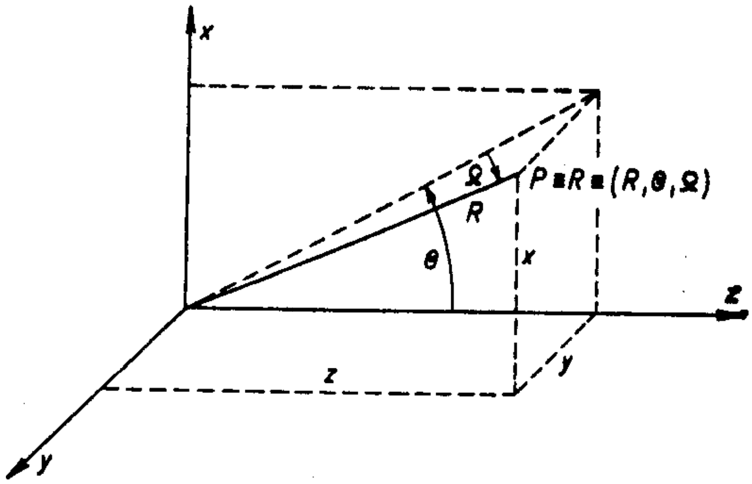

Fig. 1 - Array coordinate system

1.1 Azimuth Pattern

In the horizontal plane, accurate determination of target angle and minimization of false targets are very important. There are three azimuth patterns to be generated, sum, difference and control, which are interdependent since they employ the same elevation boards and some of the same power divider networks. The sum pattern parameters determine antenna length. The sidelobe level could be theoretically achieved using a Taylor distribution. However, the central elevation board of the array has to be fed with less power due to the form of the feed network and the interrelation of the sum and control patterns. Moreover, manufacturing tolerances cause perturbations of amplitudes and phases and increase the sidelobe level.

For integration of SSR and primary radar antennas, some compromise design should be done. Therefore, 27 elevation boards with spacing of 198 mm have been used. The optimum (narrowest) beamwidth for a given sidelobe level occurs when all sidelobes are of equal level. The ideal Taylor line source, although unrealizable, provides such a pattern. For sum pattern design, the realizable amplitude Taylor distribution with uniform phase according to (3), (4), (5), (6) has been computed with -40 dB maximum sidelobes and $\bar{n} = 6$.

To create three azimuth patterns, it is necessary to modify the Taylor distribution and a feed network. It was proved that the same amplitude and phase distribution can be used for edge elements (n = -13, -12, ... , -2, 2, 3, ... , 13) both for the sum and control SLS and difference and modified the central three element distributions (for n = -1, 0, 1). That is an acceptable design with the feed network shown in Fig. 2. A Wilkinson power divider and branch-line couplers are designed using stripline transmission lines (7), (8).

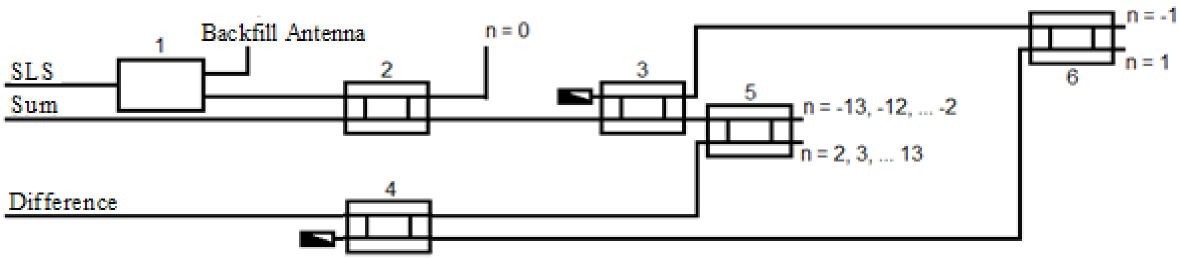

Fig. 2. - Feed network. 1 – Wilkinson power divider, 2 to 6 Branch-line couplers

The resulting distribution modifications are results of optimizations considering properties of all three beams (Sum, Difference and SLS). This distribution is very important to keep sum sidelobe level as low as possible and simultaneously to achieve the higher efficiency (gain). In fact, the mentioned modification increases slightly the sidelobe level.

The resulting radiation patterns (or better array factors) considering efficiencies (directivities) and the backfill antenna are shown in Fig. 3. It is clear that for sum sidelobe region, the SLS beam pattern is approximately greater by 20 dB than the sum beam pattern. That is sufficient for sidelobe suppression. For near axis angles the SLS beam is lower by 28.5 dB than the sum beam for angles in vicinity of $\omega = 0^{o}$. That is satisfactory as well.

The radiation patterns are given both by array factor and element patterns. That will decrease levels both for elevation as well as azimuth pattern. Considering that the individual element gains g_e are the same the gains of individual beams are governed by computed efficiencies. Obviously, the gains will be decreased by feed network losses.

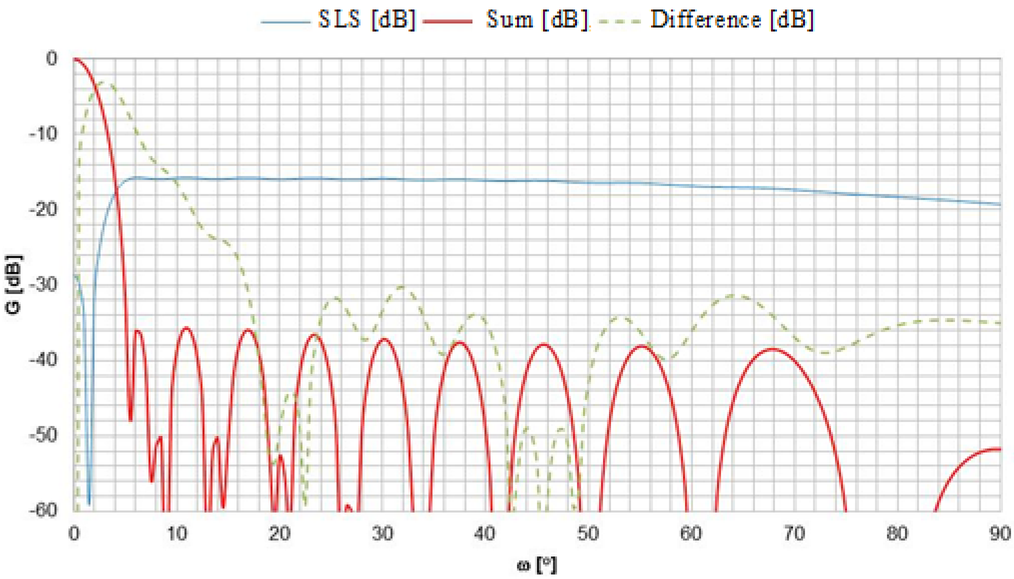

Fig. 3 - Array factors of individual beam considering efficiencies (directivities) and the backfill antenna for f =1,06 GHz

1.2 Elevation Pattern

The SSR antenna design considers 8 elements with spacing of 180 mm for vertical network due to primary radar antenna and horizontal plane level of -2 dB. To compute amplitude and phase distributions, a Woodward synthesis has been used (3), (4), (5), (6). In fact, the Woodward synthesis is not optimal and another method could be used but from tolerance point of view the Woodward synthesis is much more suitable. Moreover, the Woodward synthesis could be easily modified, i.e. sample values could be changes thanks to fact that the synthesized pattern exactly equals the desired pattern at the sample points due to the orthogonality of the component beams.

The array factor design is shown in Fig. 4. The used values for pattern sampling optimization are given by crosses, the dashed line shows values corresponding to sampling and the solid line is shifted array factor [dB] for 8 elements with spacing of 180 mm.

The elevation coverage diagram for 8 elements with spacing of dx = 180 mm is shown in Fig. 5. The solid line shows values without ground reflection effects. The dashed line depicts ground reflection effects considering very rough assumption for reflection coefficient of $\Gamma = -1$, which is approximately valid for $\theta < 4^0$. Therefore a “null” for angle θ about 3^0 is extremely doubtful. In fact, the absolute value of reflection coefficient for vertical polarization is sharply decreasing. Moreover, the random changes, such as terrain variations and vegetation, could be substantial.

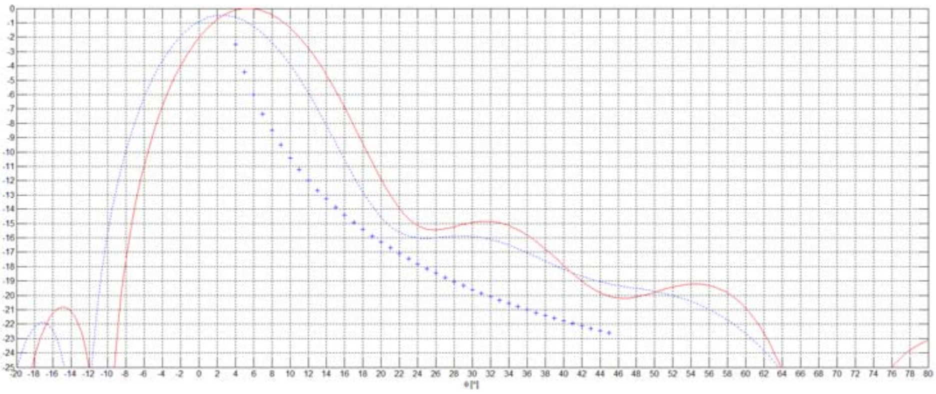

Fig. 4 - Elevation array factor for N = 8 elements, f =1,06 GHz, dx = 180 mm

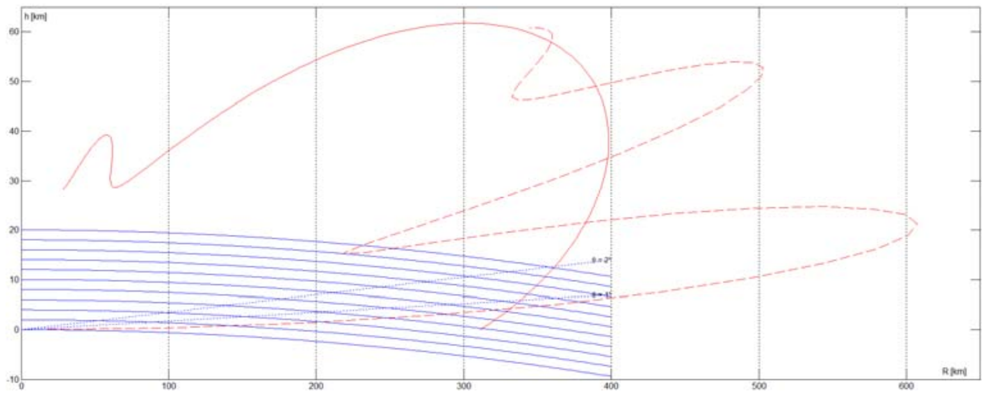

Fig. 5 - Elevation coverage diagram for 8 elements with dx = 180 mm and f =1,06 GHz

2. FEED NETWORK

The SSR antenna consists of 216 irradiating elements, arranged into 27 vertical columns of 8 elements. The vertical distribution of amplitude and phase creating antenna elevation pattern, common to all three horizontal beams are accomplished by 27 identical vertical feeders. The vertical feeders are fed by a 3in/27out horizontal feeder generating the three beams: the sum, the difference and the SLS ones. Due to low insertion loss requirements the whole SSR antenna feeder is designed basically as a suspended stripline network.

2.1 Vertical feeder

The vertical feeder consists of 7 branch line couplers (see fig. 6) of different power divisions connected by striplines, providing the appropriate phase and amplitude distribution.

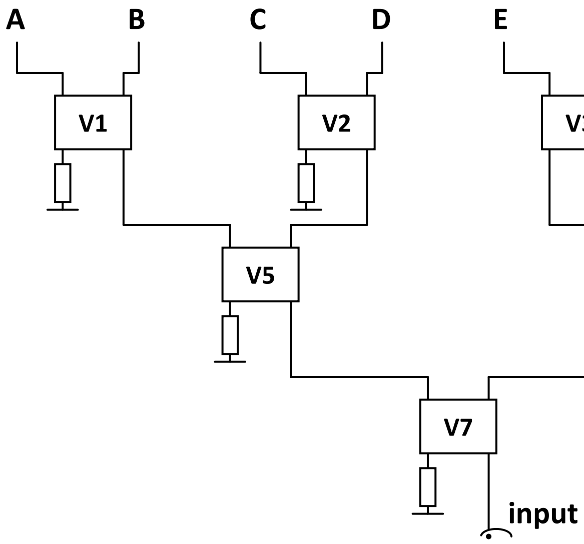

Fig. 6 - Block diagram of one vertical feeder. The ports A, …, H are connected to the antenna elements.

The vertical feeders are mounted at the front face of the primary radar antenna so there are severe constrains on their dimensions. To save the scare space the branch line couplers should have been dramatically distorted obtaining finally the form, shown in the Fig. 7. The actual reference planes of the line junctions were determined from the reflection coefficients S_{ii} minima frequencies measurement on the individual dividers.

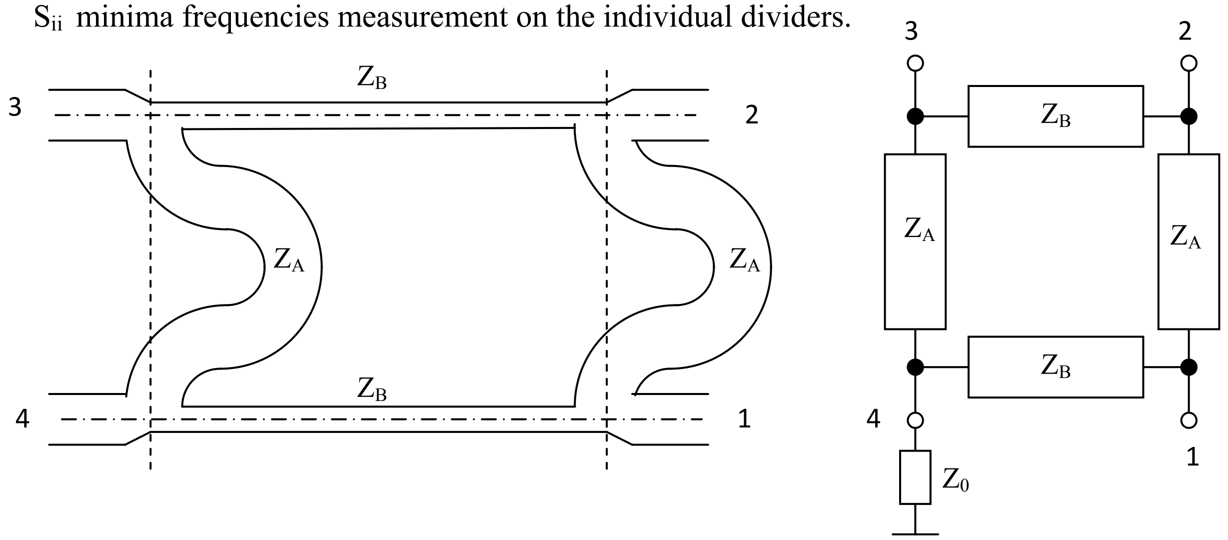

Fig. 7 - The vertical feeder branch line couplers of the distorted form.

The vertical feeder dimensions minimization led also to a two layer design sketched in the Fig. 8. In the first layer the dividers No. 1 to 4 are placed, which outputs are directly connected to the eight antenna elements. The second layer contains the rest three dividers and the feeder input port. Thanks to the all described modifications the vertical feeder is only 85 mm in depth.

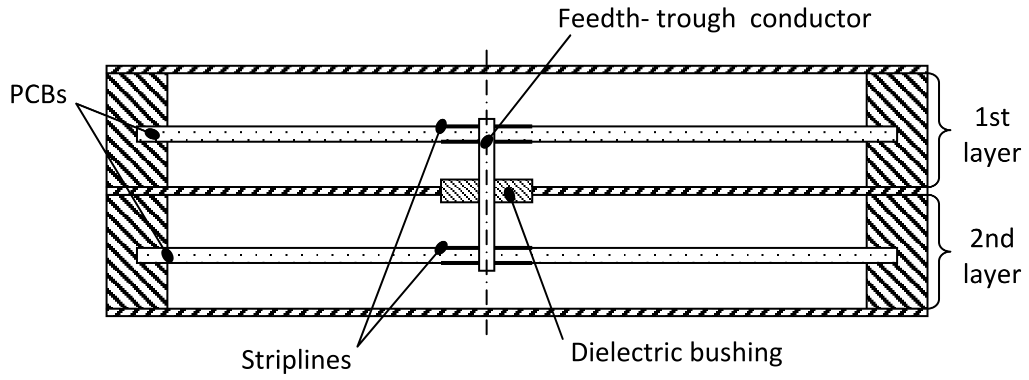

Fig. 8 - The layered design of the vertical feeder.

2.2 Horizontal feeder

The horizontal feeder network comprises 27 power dividers of various types. It is segmented into three blocks: one central feeder block and two lateral ones. The central block diagram is shown in the Fig. 2. Consisting of six power dividers/combiners it combines three inputs for sum, difference and SLS beam signals and distributes them to six output ports for three central vertical feeders, for the two lateral feeder blocs and for the backfill antenna. Only the divider No. 1 is a Wilkinson type power divider, the rest ones are of the branch line type.

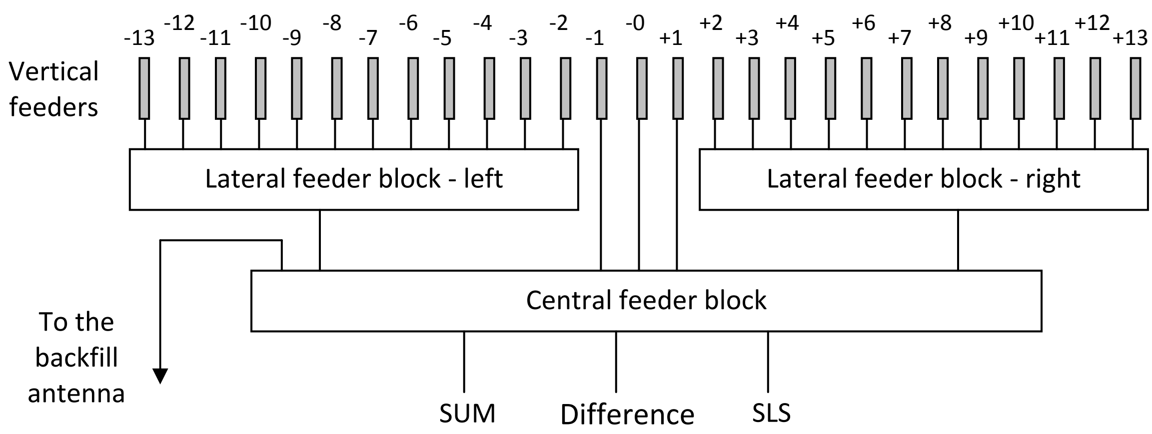

Fig. 9 - Schematic diagram of the horizontal feeder

The two lateral feeder blocks are identical but mirror-oriented to provide a symmetrical excitation of the vertical feeders (Fig. 9). The lateral feeder block is an 1/12 divider and consists of eleven branch line power dividers. Due to a non-uniform signal amplitude distribution at the twelve outputs the branch line dividers output power ratios have a large span from 3 to 11 dB. Particularly the dividers with low coupling are extremely sensitive to tolerances of the high impedance segments Z_B (see the Fig. 7). Also the divider network is arranged in a quite nonstandard way.

CONCLUSION

In the paper the MSSR antenna design is described. To create three azimuth patterns, it is necessary to modify the Taylor distribution and a feed network. It was proved that the same amplitude and phase distribution can be used for edge elements both for the sum and control SLS and difference and modified the central three element distributions. The resulting array factors considering efficiencies (directivities) and the backfill antenna are shown in Fig. 3. The Woodward synthesis has been used for elevation pattern as it is much more suitable from tolerance point of view. The elevation array factor design is shown in Fig. 4.

Severe dimension constrains on antenna parts, following from the integration with the primary radar antenna requirements were solved using distorted form of branch line couplers and the layered feeder structure.

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