Orbiter Environment at S- and K_u-Band Frequencies

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Detailed measurements of the electric field strength associated with the K_u-band radar and S-band communication link were made by the Plasma Diagnostics Package (PDP) on STS 51F. These measurements were made while the PDP was attached to the Remote Manipulation System arm and again while the PDP was released as a subsatellite. The results indicate that cargo elements that remain inside of the scan limits of the radar should experience fields less than 2 V/m and that elements that may encounter the main beam can use 300 V/m as a design guideline with adequate safety margin. S-band fields tended to be several dB lower than worst case predictions. Safe design practice indicates that an electric field $E = 100/r$ (r in meters) should be used as a guideline for deployable systems. S-band electric fields within the cargo bay envelope should be < 2 V/m even with edge diffraction effects and reflections from other payloads taken into account. The absolute accuracy of these measurements is ~ 2 dB.

I. Background

THE Space Shuttle Orbiters were designed to haul cargo into orbit as well as retrieve it from orbit. Because the cargo can be extremely varied in its application, a great effort has been made to define as much of the environment as possible in and near the Orbiter in launch, orbit, and landing phases. By knowing precisely what environment to expect, engineers can appropriately design the payloads to operate safely and reliably within that environment.

The Plasma Diagnostics Package (PDP) is a cluster of fourteen instruments designed primarily to define the way in which the Orbiter perturbs the natural plasma environment. A complete description of this instrumentation may be found in Shawhan.[1] Since plasma-wave instruments were part of the cluster in the PDP, measuring electric and magnetic fields to approximately 200 kHz, it was logical to use the PDP to measure Orbiter-induced electromagnetic interference (EMI) as well. The wave measurements were therefore extended in frequency range to measure fields generated by the Orbiter's intentional transmitters. An S-band receiver was added specifically to measure field magnitudes due to the PM and FM communication link. Shawhan[2] summarizes the EMI results obtained from the PDP wave instruments on the third test flight of the Orbiter Columbia (STS-3).

Detailed measurements at S-band communication frequencies on STS-3 indicated that field strengths were on the high side of predictions but with an uncertainty factor that made a refined set of measurements desirable.[3] The S-band detector system was upgraded, and a receiver was added that had the ability to measure the fields of the K_u-band integrated radar and communications link. A detailed description of this hardware, referred to as the KUSR, may be found in Murphy[4] and a brief overview is given in Sec. II.

Upon completion of the hardware calibration and integration, the PDP was reflown on Challenger 51F (Spacelab 2), and a number of specific experiments were implemented to characterize the S-band and K_u-band links. These experiments are described in Sec. III.

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Before engaging in a detailed discussion of the experiment and results, it will be appropriate to review briefly the Orbiter's S-band and K_u-band communications system.

Challenger S-Band Communication Link

There are several communication systems in the S-band frequency range, but only the one with highest power output is of concern for our measurements. This system, the CW phase modulated link, operates at a frequency of 2287.5 MHz through the four S-band "Quad" antennas located above and below the cabin area. It should be noted that the configuration of the antenna beams has changed from that which was measured on the STS-3 mission. The configuration on the Columbia allowed the selection of one of four antenna beams mounted in equal quadrants at four points around the crew cabin. For the Spacelab 2 mission, the Orbiter Challenger had been modified to provide eight possible antenna beams.

The eight beams are created by the use of four sets of waveguide slot antennas that are centered about four points around the circumference of the cabin area. See Table 1 for the location of these antennas in Orbiter body axis coordinates. By properly phasing each set of antennas, a broad beam can be made to point slightly forward or slightly aft of the Z axis. Since the antennas are located at angles of approximately 45 deg to the X-Y and X-Z plane, they are referred to as upper left (UL), upper right (UR), lower left (LL), and lower right (LR) antennas. (See Fig. 1 for a definition of the coordinate system used.) In addition, the designation "F" or "A" (e.g., ULA) is added to indicate, for a given antenna, whether the forward or aft pointing beam is selected for a specified antenna.

Table 1 Quad antenna locations[a]

	X	Y	Z
UL	−551	−71	−472
UR	−551	+71	−472
LL	−556	−96	−295
LR	−556	+96	−295

[a]Given in Orbiter body axis coordinates.

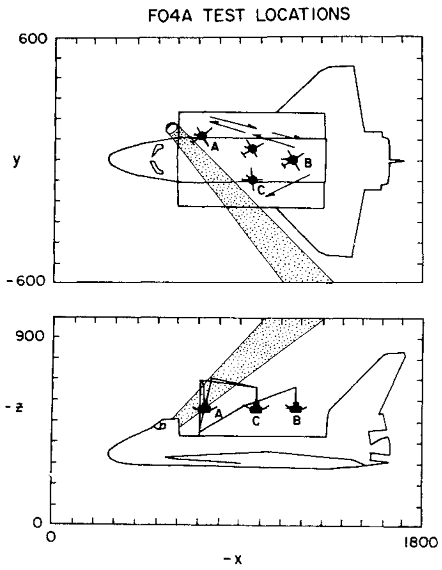

Fig. 1 Schematic representation of the FO4A sequence.

The high-frequency mode (2287.5 MHz) has the highest output power of all the possible S-band links and was selected when the KUSR made its measurements. The maximum measured output power of the high-frequency PM link transmitter is 163 watts (52 dbm). With 3.5 dB minimum cable loss, the maximum power available to the antenna is approximately 73 watts. (Measured cable loss varied from -3.5dB to -3.9dB.) Considering the maximum predicted gain of antennas at boresight is 7.1 dB (power ratio 5.12), the maximum expected field in a limited solid angle would be

$$E(V/m) = (1/r)[(1/4\pi)P \cdot G \cdot Z]^{1/2}$$

where P = transmitting power (watts), G = antenna gain, Z = free-space impedance, 377 Ω and r = distance (meters).

It is this worst-case electromagnetic field estimate that the experiment attempts to verify.

Shuttle K_u-Band Radar and Communications System

Since the Orbiter uses the same amplifier and parabolic antenna for operation of its TDRS data link (15.0034 GHz CW) and its radar link (five frequencies between 13.779 GHz and 13.987 GHz pulsed) and their peak output is essentially the same, it is sufficient to measure one or the other to determine worst-case fields. The radar field is linearly polarized in its passive mode, whereas in the communication mode the polarization is circular. Because of the flexibility of the radar system and the fact that it will be tracking the PDP while it is a free flyer, it was decided to make all measurements in radar mode. All details of the radar system may be obtained from Ref. 5 but are given below in a summary form.

The K_u-band radar and communications system is folded inside the payload bay for ascent and entry and deployed over the starboard sill next to the forward bulkhead when in use. Details of the antenna pattern and its predicted fields will be discussed in Sec. IV. The antenna has a 2-axis positioner and is pointed by rotation around a pivot point 21 inches from the antenna centroid when tracking satellites but employs an adjustable "obscuration mask" to prevent its pointing at certain elements of the Orbiter and into the payload bay.

The radar system is designed to track a standard Swerling target from approximately 30 m (100 ft) to 35 km (20 n.mi.). Since this is a range-gated radar, both the pulse width (pw) and pulse-repetition frequency (prf) are variable depending on the target distance. Table 2 lists the various pulse widths and prf's available depending on target distance and whether the radar is in its search or track mode.

In order to minimize scintillation effects, the radar frequency is automatically varied over the band indicated above

Table 2 Signal parameters for RR radar and radar power output

Mode	RR Radar		
	Range (n.mi.)	prf	pw (μs)
Track	> 9.5	2987	33.2
	3.8 — 9.5	6970	16.6
	1.9 — 3.8	6970	8.3
	0.95 — 1.9	6970	4.15
	0.42 — 0.95	6970	2.07
	<0.42	6970	0.122
Search	>0.42	2987	66.4
	<0.42	6970	0.122
	Radar Power Output		
Mode (Radar)	Output Power Level	Maximum Near Field (V/m)[a]	Far Field[b]
Hi power	70 watts	280[c]	2320/R
12 dB pad	4.4 watts	70	583/R
24 dB pad	0.3 watts	17	146/R
TWT bypass	~ 4 mwatts	3	26/R

[a]Maximum in Communication Mode is 300 V/m. [b]Begins at ~ 77 m from dish. [c]In Fresnel Zone extending to ~ 10 m.

in steps that are 52 MHz apart giving the following operational frequencies: 13.779, 13.831, 13.883, 13.935, and 13.987 GHz. This frequency switching happens rapidly compared to our KUSR measurement cycle and will not be important in data analysis.

Because there is a wide range in the possible return power (depending on target size and distance), it would be difficult to design the front end of the radar receiver section to handle such a dynamic range. Thus several output power levels are available. The power levels of these modes and the predicted field strength in the main beam at a distance of 100 m are contained in Table 2. The output power depends not only on the distance to the target but also on the radar mode selected. By choosing the proper mode, the PDP was able to make measurements of the radar beam even when it was too close to the orbiter to be tracked by the radar.

II. KUSR Instrumentation

The K_u-band/S-band receiver (KUSR) built and integrated into the PDP for the Spacelab 2 mission was designed and calibrated with the goal of measuring the S-band and K_u-band fields to a precision of 1 dB. This goal, since it was quite ambitious, could not be achieved, but accuracies on the order of 2 dB were attained. Although a complete and detailed description of the system is not within the scope of this paper (see Ref. 4), it is appropriate for the reader to have some basic understanding of the instrument.

The K_u-band subsystem consists of an optimal gain conical horn coupled to two orthogonal linear probes in a circular waveguide. The RF probe output is converted to DC through a zero-bias Schottky detector. This detector output is then routed to dual amplifier/peak detector systems, one high gain and one low gain. The outputs of both channels are multiplexed with S-band data and sampled by the PDP telemetry encoder at the rate of 10 Hz. Table 3 contains data on the sensitivity of this system.

The S-band subsystem differs somewhat from that which was flown on the STS-3 mission. A broadband, low-gain, ridged-guide horn was used for an antenna. Output was mixed to IF with a 2.20 GHz L.O. and the signal detected by both a linear detector (diode type), where output voltage was proportional to measured E-field, and a log detector. In front of the log detector was a bank of four filters; 25-65 MHz, 65-165 MHz, 165-400 MHz and 400-800 MHz, whose outputs were multiplexed to the log detector. Since we are only interested in the 2287.5 MHz PM link, only the output from the second filter (65-165 MHz) will be used in this report.

The test program for calibration of the KUSR was designed such that all absolute calibration ultimately depended on the accuracy of three things: 1) the repeatability of a measurement setup, 2) the absolute calibration of a power meter, and 3) the absolute accuracy of a standard gain horn. Table 4 delineates the instrument calibration error budget.

Calibration of the K_u-band subsystem was done for othogonal linear polarizations, for five radar frequencies, and at all nominal pulse widths expected. These calibrations were performed in an anechoic chamber and compared to data from a standard gain horn. The system is slightly less sensitive at the lowest pulse width (0.122 μs) but becomes flat above that 1.5 μs. There is no frequency sensitivity because the radar changes frequencies rapidly compared to the peak detector sample rate. Only the frequency to which the system is most sensitive determines the output response on orbit.

By combining output from both polarizations, the total E-field may be determined independently of rotation about the line-of-sight axis to the source.

The S-band system was also calibrated in an anechoic chamber against a standard gain horn and its sensitivity is summarized in Table 3.

Both the K_u-band and S-band antenna patterns were plotted in azimuth and elevation so that measurements made at angles other than boresight could be reliably used in the analysis. In all cases these chamber measurements were made with the KUSR integrated into the PDP and with the PDP in its flight configuration.

III. Experiment Objectives

As with all experiments on Spacelab missions, detailed procedures, requirements, and configurations are determined far in advance of a mission and then timelined as resources will allow. The following Functional Objectives (FO's) defined the goals of the KUSR experiment on PDP. These are met either by maneuvering the PDP on the RMS or by making measurements of the generated fields while the PDP is some distance away as a free-flying satellite.

F04A—K_u-band EMI

The RMS sequence pictured in Fig. 1 is used to move the PDP along the payload bay at a level near the top of the cargo doors. (The coordinate system used in Figs. 1-3 is the Orbiter Body Axis System (x/foreward, y/starboard, z/down). The origin of this system is the nose of the external tank.) The radar dish is pointed over the payload bay (elevation +60, azimuth +50) at the edge of its allowable scan limit. The shaded portion of Fig. 1 depicts the beam at this scan angle. Low-power mode is chosen for the first part of the scan while the PDP continuously points its receiving antenna at the dish. During the last half of the scan, the PDP is rotated and points its receiving antenna at the vertical stabilizer allowing possible measurement of reflected fields. High-power mode was selected for this segment of the scan. This FO allows the instrument to characterize the worst-case electric fields expected near the cargo-bay envelope.

K04B—K_u-band Antenna Pattern—Near Field

The RMS sequence depicted in Fig. 2 is used to make direct measurements of the near-field radar beam. The radar is pointed up the -Z axis of the Orbiter, and the PDP scans along the beam axially from approximately 2.5 m (8 ft) to 10 m (35 ft).

Table 3 K_u-band and S-band sensitivity

K_u-Band, Single Channel	
Hi gain 13.887 GHz	2.07 μs pw
0.8 V/m	4 V/m[a]
Lo gain	
3.5 V/m	63 V/m[a]
S-Band	
Log detector	2287 MHz
−42 dB V/m	+29 dB V/m
(0.008) V/m	(28 V/m)
Linear detector	2287 MHz
−18 dB V/m	+13 dB V/m
(0.126 V/m)	(4.45 V/m)

[a]Variation exists between the 2 polarizations. These data are typical.

Table 4 Instrument error budget

Source of Error	Magnitude of Error (dB) K_u-Band	S-Band
Setup repeatability	±0.5	±0.5
Gain of standard horn	±1	±1
Calibration of detector	±1	±1
Mismatch detector/ antenna	±0.5	±0.5
Sensitivity	±0.25 (typ)	±0.6 (typ)
Temperature correction	±0.2	±0.5[a]
Total RMS error ±1 dB desired	±1.6 dB	±1.76 dB

[a]Log Detector was not calibrated over temperature.

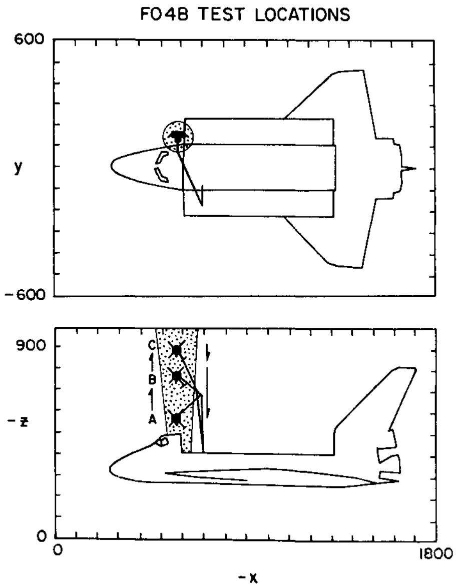

Fig. 2 The 4B scan sequence used to determine near-field strength of the radar beam.

At distances of 8 m (25 ft) and 10 m (35 ft)(points B and C in Fig. 2), the PDP is moved in X and Y to scan the beam radially. This scan was performed with the radar in both low and high power.

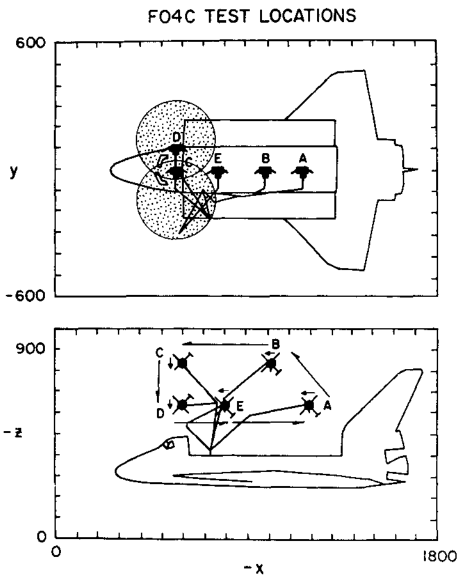

Fig. 3 The 4C scan sequence used to survey fields associated with Quad aft beams (2287.5 MHz.).

F04C—S-band Fields Near the Payload Bay

Figure 3 illustrates the RMS sequence used for this field survey. This is essentially a repeat of the experiment performed on STS-3. The scan is executed twice, once with the ULA beam selected (2287.5 MHz) and once with the URA beam selected. The small arrows in the figure indicate the pointing direction of the S-band horn.

F08—S-band Antenna Patterns

Figure 4 illustrates the objective that came to be called the "F08 roll." Since there are eight possible antenna beams on the Orbiter, it is desirable to get as much pattern information as possible on all of them. The PDP was a free-flying, spinning satellite, and the Orbiter was stationkeeping at ~ 90 meters along the velocity vector in front of PDP. Once stationkeeping was established, the Orbiter started a slow roll about its X-axis (0.75 deg/s). By selecting the proper antenna, a 90-deg scan of each of the eight beams was performed over a period of two complete rolls.

Another KUSR measurement goal, although not flight-test data are within approximately 3 dB of the theoretical prediction and in all cases are lower than the predicted value. Error bars on the PDP measurements would be ± 1.6 dB. easily obtained because the orbiter tracks the PDP during its free-flight at distances up to approximately 0.5 km.

IV. Results of K_u-Band Measurements

F04A was executed only one time, but the results are significant in that they provide guidelines for the EMI design specifications of hardware to be carried in the payload bay. During the first half of the scan depicted in Fig. 1 (A-B-C), the antenna, positioned against software limits at az-50 el-60, was operated in low power. No fields above the level of instrument sensitivity were detected (< 2 V/m) even though the PDP receiving antenna was directed toward the K_u-band radar dish. It should be noted that the original goal of pointing the radar directly at the vertical stabilizer was not achievable. Some higher reflected fields may have been expected in that case. During the second half of the scan (C-B-A), the radar antenna was operated in high-power mode. The only time any field above noise level was detected was at position C, where the PDP measured fringe fields associated with the beam per se. It should be noted that during this second half of the scan,

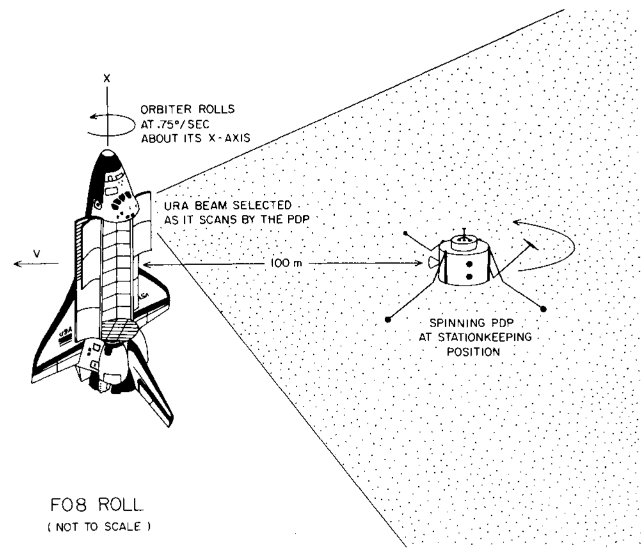

Fig. 4 Configuration for the F08 roll.

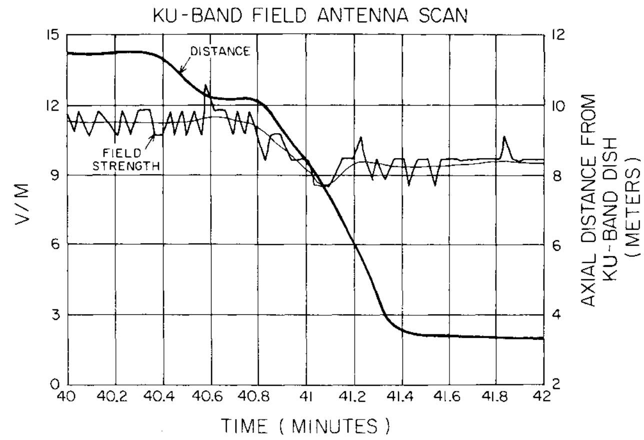

Fig. 5 Field strength measured during F04B scan.

the PDP receiving antenna was pointed in the general direction of the aft cargo bay and vertical stabilizer to look for reflected fields. The fact that no signals were detected implies that fields associated with power reflected from developing sidelobes many degrees from the main beam are negligible. F04B results discuss off-axis intensity in more detail.

Results of the above experiment would seem to confirm that instruments operating entirely within the obscuration mask or scan limits should not experience fields in excess of 2 V/m. Within the primary beam no reflections from other payload bay elements would seem to contribute enough to the field intensity to be of concern if instruments are not sensitive to 2 V/m fields. However, any instrument that is operated outside of this protective envelope should design to fields associated with the main beam.

The purpose of F04B was to measure the fields associated with the near-field beam. Figure 5 is a plot of the intensity of the K_u-band electric field in low-power radar mode and the axial distance from the center of the radar dish as a function of time for the first execution of F04B. As can be seen in the figure, the field is not strongly dependent on distance along the beam center. The intensity has a minimum at a distance of ~ 7.5 m and a broad maximum of ~ 11-12 V/m from 10-12 m. Although two scans were done with this RMS mode, only the first scan, done in low-power mode, is plotted in Fig. 5 since the second scan, which was in high power, saturated the instrument when it was on axis of the antenna. Assuming the specified 24 dB difference between low and high power shown in Table 2, the maximum expected electric field in the near-field beam interpolated from the data would be ~ 190 V/m.

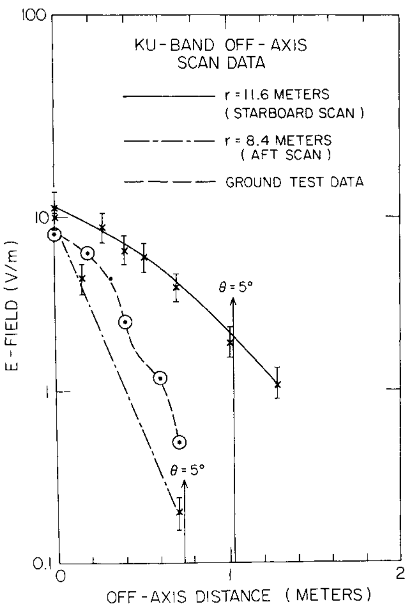

Fig. 6 Near-field off-axis scan data.

Figure 6 illustrates the radial dependence of the electric field intensity as the RMS scanned the PDP perpendicular to the beam axis. The figure is a compilation of data from 2 scans. For reference, data taken during ground testing[6] at a distance of 8.4 m is also shown in Fig. 6.

A look at the raw data taken during the second F04B scan, which had the radar in high-power mode, reveals some interesting characteristics. Figure 7 plots the total measured field as a function of time. The two large dips in the field are the manual X and Y off-axis scans. The actual fields plotted are incorrect except during these X and Y scans because the instrument is in saturation (the actual field should be ~ 190 V/m based on low-power scan data). Several conclusions can be drawn from these data. The apparent increase in the total field at the beginning and end of the Y-scan indicates a shift in the polarization. This is noticeable because of a difference in sensitivity of the orthogonal detectors. At an angle of 6.5 deg away from the main beam, the field is still 18 V/m, yet a closer distance and 5 deg from the beam, the field is below the level of sensitivity of the low-gain detector. It is also interesting to note the apparent variation in intensity from time = 28 to time = 32. This change (a result of increasing the distance from the dish) is not only a real amplitude change but also indicates a polarization shift. The X-scan is noteable because small "sidelobes" are beginning to form at this location. It is not clear if these are real or an artifact of multiple reflections between the probe (PDP) and the dish.

Additional measurements of the Orbiter's radar were obtained during the free-flight portion of the PDP's experiments. At distances greater than ~ 200 m (640 ft), the radar is in high-power mode during passive track and additional data points on the beam intensity were obtained at several distances. Figure 8 is a plot showing the superposition of a theoretical 25 dB Taylor distribution, Rockwell ground test data, and the points obtained both during F04B and free flight. [Figure 8 ground-test data ran 7.26 dB below a "hot" (hypothetical) system that would have 1) the highest output power of any production TWT, 2) the least observed waveguide loss, and 3) the highest antenna gain ever measured. There are natural variations in these parameters between systems.] The flight-test data are within approximately 3 dB of the theoretical prediction and in all cases are lower than the predicted value. Error bars on the PDP measurements would be ± 1.6 dB.

Discussion of the comparison between the measured values for K_u-band electric fields and design specifications will be continued in the summary section.

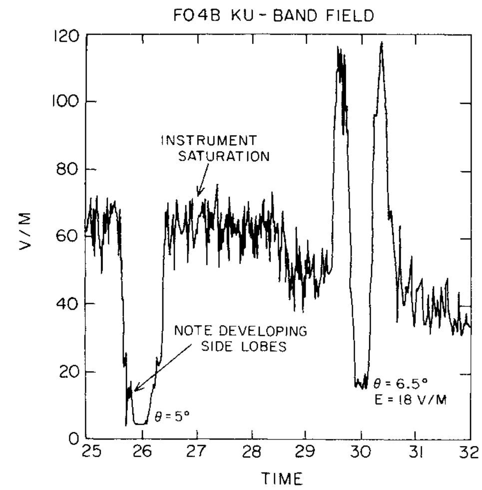

Fig. 7 Magnitude of the electric field as a function of time during the high-power FO4B scan.

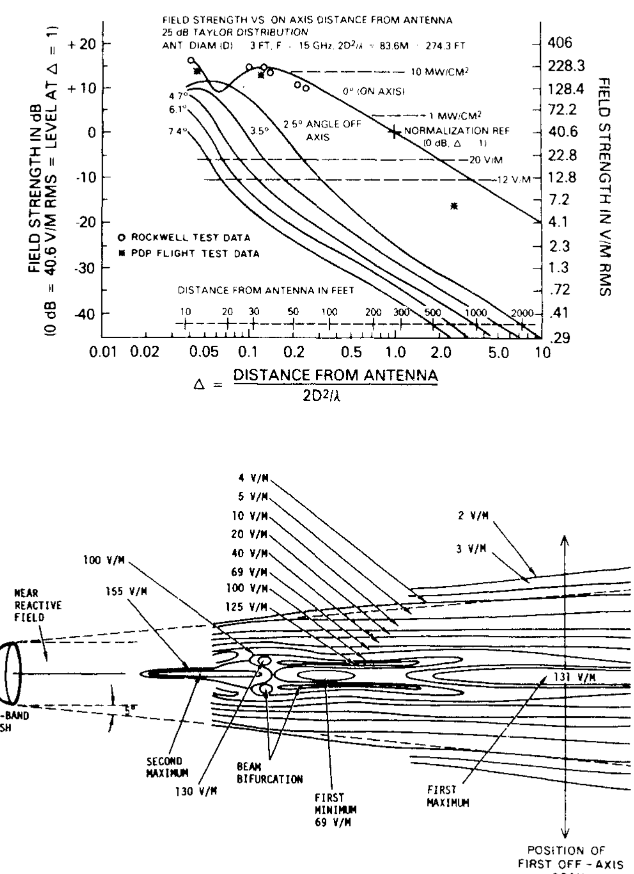

Fig. 8 Comparison of flight data to ground test results.

V. Results of S-Band Measurements

RMS test objective 4C, which was discussed in Sec. III, resulted in tabulated values of electric field intensity at several locations in and over the cargo bay. The RMS sequence was executed twice with either the URA or ULA quads selected since they produce the worst-case fields in and around the cargo bay. Table 5 summarizes the results of the measurements at each of the test locations shown in Fig. 3. These data have been corrected for the receiving antenna directivity, but it should be noted that the receiving antennas are linearly polarized and the transmitting antennas (quads) are circularly polarized. This imples that the total E-field at boresight is 3 dB greater than we measure.

Table 5 FO4C Summary

RMS Point (Fig. 3)	Distance from XMTR (m)	Angle from boresight (deg)	Measured field dB (V/m)	Antenna directivity correction (PDP) dB	Equiv. E-field V/m	Antenna Directivity correction (XMTR) dB	Far-field constant[a] k = Er
			Upper Left Aft				
A	16	70	−4	1.35 ± 0.1	0.74	6 ± 1	23.5
B	14.3	58	4	2.7 ± 0.5	2.2	6 ± 1	61.7
C	9.2	54	11	1.05 ± 0.1	4.0	5 ± 1	65.1
D	6.0	86	5	5.8 ± 1	3.5	8.5 ± 1	55.4
E	6.9	64	4	3.5 ± 1	2.4	6 ± 1	32.6
			Upper Right Aft				
A	16	69	−6	1.3 ± 0.1	0.58	5 ± 1	16.6
B	14.3	56	2	2.5 ± 0.3	1.7	4 ± 1	38
C	9.3	51	8	1.2 ± 0.1	2.9	2 ± 0.5	33.8
D	4.1	31	17	1.15 ± 0.1	8.1	1 ± 0.5	37.4
E	7.0	60	8	2.4 ± 0.5	3.3	4 ± 1	36.7

[a]Not corrected for polarization loss.

Column 8 in Table 5 shows the value of $k = E \cdot r$ calculated for each measurement point, where r is the distance between transmitter and receiver. Note that for measurement angles far from boresight (points A and E for URA and points A, D, and E for ULA), there tends to be some divergence from the trend. This is consistent with the purity of the polarization from the transmitting antenna degrading at angles from boresight. Measurements taken at small angles from boresight give the best indication of the output of the transmitting antennas; however, measurements at larger angles from boresight do provide a realistic assessment of the fields encountered by a single linear polarized aperture at these locations. It would be wise for the designer to assume all of the power from the transmitting antenna, P_t, not P_t-3 dB, is available to excite an aperture of any given orientation at these points in the cargo bay.

Measurements made during Orbiter back-away after PDP release provide the best measure of the $E \cdot r$ constant. Figure 9 is an illustration of the data taken during this maneuver. (These data have not been corrected for polarization loss.) The PDP was released from the RMS at 213:00:10:00; at 213:00:12:05 the Orbiter began a series of thruster firings that caused it to separate from the PDP at a rate of ~ 0.5 ft/s. Within 30 seconds after release from the RMS, the PDP began to slowly spin up. This generated the spin modulation evident in the data of Fig. 9. Figure 9 has been fitted to a k/r curve, where the best-fit value of k is 31.1 ± 0.5. Correcting for the 3 dB polarization loss, the expected value of electric field from an upper quad antenna (it is not known if it was ULA or URA) is $E = 62/R$. These data are in close agreement with FO8 roll data for the ULA antenna discussed below.

In order to obtain measurements on all eight antennas, the FO8 roll maneuver (see Sec. III) was performed at a distance of approximately 90 meters from the Orbiter. Figure 10 illustrates the data taken during this objective. (The peaks are a result of the 13 s spin period of the PDP modulating the receiving antenna gain.) The PDP was located at a distance of about 90 m behind and slightly to the aft of the Orbiter. The roll maneuver about the Orbiter X axis thus produced a good principal plane scan of the aft beams but did not pass through the center of the forward pointing beams. The minimum angle

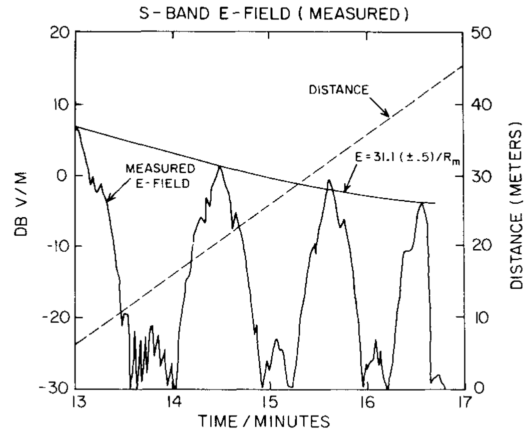

Fig. 9 S-band data from Orbiter back-away maneuver.

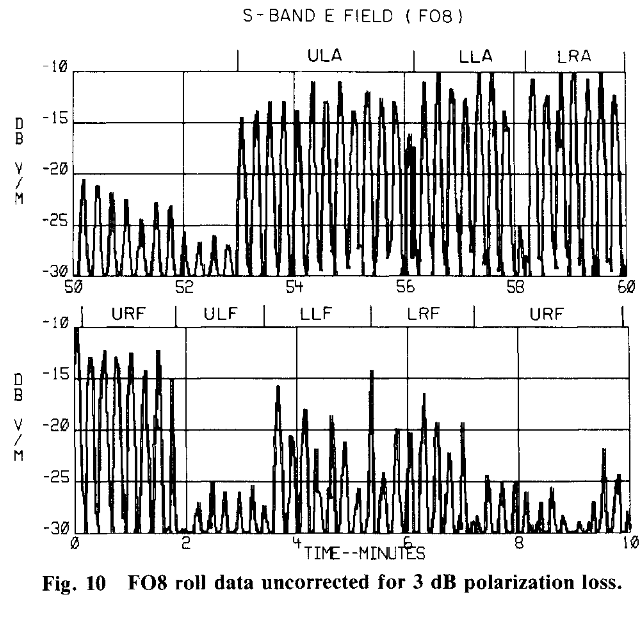

Fig. 10 FO8 roll data uncorrected for 3 dB polarization loss.

Table 6 FO8 S-band fields

Antenna Selected	Peak field measured dB (V/m)	Distance (m) (± 5)	Angle from boresight[a] (deg)	k = E·r	+ 3 dB polarization loss (XMTR)
ULA	−10	93	0 ± 2	29.4	58.8
LLA	−9	92	0 ± 2	32.6	65.2
LRA	−9	91	2 ± 2	32.3	64.6
URA	−12	86	3 ± 2	21.6	43.2

[a]Closest approach of pattern cross section to transmitter boresight.

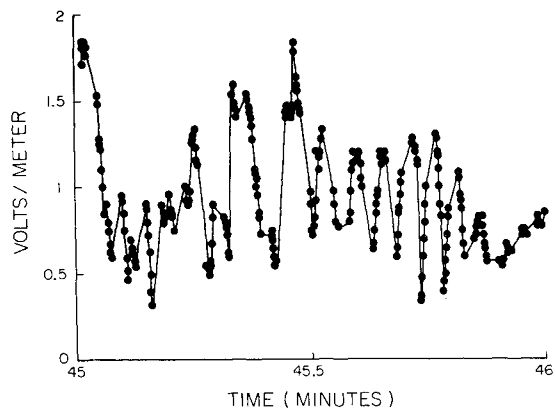

Fig. 11 Standing wave pattern observed as the PDP was moved from location D to E of FO4C scan.

to boresight for measurement of the forward beams was ~ 40 deg. This is evident in Fig. 10 from the lower intensity for all of the forward antennas. Using the ground-test data[7] for antenna patterns illustrated in Fig. 10, a correction for directivity of the transmitting antenna can be made and an estimate of boresight intensity obtained. Table 6 summarizes the results, corrects for the 3 dB polarization loss, and provides an estimate of the worst-case fields for the aft beam of each antenna at this measurement distance.

An additional topic of interest for S-band fields in or near the cargo bay is how much electric field enhancement can be expected due to reflections from payload elements in the cargo bay and possible diffraction effects associated with the edge of the forward bulkhead. The RMS scan for FO4C yielded interesting results in this regard. Figure 11 is a sample of S-band data taken during FO4C scan from point D to E. The quasi sinusoidal variations observed can be explained by the PDP being moved through a standing wave pattern resulting from interference of multiple sources. (This standing wave pattern is not observed external to the cargo bay.) It is not possible with the complex geometry of the payload bay elements of 51F (Spacelab 2) to discriminate possible multiple source reflections, which would produce a standing wave pattern, from the diffracted fields that could also be present.

If we assume that this pattern is due to one primary and one secondary source, the worst-case VSWR observed indicates that the secondary source has a power approximately 20% that of the primary source. Since these observations are highly dependent on position within the cargo bay envelope and would, of course, be dependent upon payload geometry, it would not be unreasonable to expect reflection enhancements to be as high as 50% over that of the primary source. Several dB margin of error over the measured E/R constant should be allowed to account for field enhancement from these reflections.

VI. Summary

For the EMC design of Shuttle payloads, several general conclusions can be gathered from the above data.

Under normal conditions, K_u-band electromagnetic fields experienced by cargo elements remaining inside the radar-scan limits set by either hardware limits or observation mask will be less than 2 V/m. Payloads that will be deployed or operated in any way outside of the mask, or those that need to operate concurrently with the radar and depend only on operational guidelines to prevent the radar antenna from pointing at them, should design to the guidelines given in the JSC, 07700, Volume XIV, Attachment 1 (ICD 2-19001). This specification lists the maximum field in the high-power beam to be 300 V/m. Experience dictates that this is probably an overestimate by ~ 50% of what fields may actually exist. Since there can be intrinsic variation in TWT output power and waveguide losses among orbiters, the 300 V/m value should be used to provide an adequate safety margin. Our measurements on Challenger can serve only to provide additional credibility to these guidelines.

S-band electric fields also tended to be shomewhat lower than worst-case predictions. Figure 10.7.2.2.6-1 in ICD 2-19001 gives worst-case fields at boresight of slightly more than $100/r$. Our measurements that have an absolute accuracy of ± 2 dB predict ~ $60/r$, which is about 4.4 dB low. This is not unreasonable since the ICD gives worst-case numbers. Safe design practice would indicate that for any point near the Orbiter payload bay, $100/r$ field prediction provides an adequate margin of safety. E-fields within the cargo bay should always be < 2 V/m even with reflections and/or diffractions taken into account.

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