RFSOC Electromagnetic Radiation Magnitude Assessment Postprint

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Abstract

Radio Frequency System-On-Chip (RFSOC), as a highly integrated, high-performance, low-power single-chip system, exhibits broad application prospects in radio astronomy, particularly in the digital backend of telescopes. Radio telescopes impose extremely stringent electromagnetic compatibility requirements on electronic equipment, and high-speed, high-frequency RFSOC generates severe radiated interference during operation. To address challenges such as numerous interference sources in RFSOC and the difficulty in quantifying radiation intensity among different sources, a radiation magnitude evaluation methodology is proposed at the component level to analyze the radiation intensity and impact of various components. Furthermore, electromagnetic radiation under different operating states of RFSOC is assessed and analyzed from an overall board-level perspective. Based on the electromagnetic compatibility design requirements of telescopes, the electromagnetic protection needs are analyzed, providing crucial technical support for subsequent electromagnetic protection measures.

Full Text

Preamble

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Evaluation of RFSOC Electromagnetic Radiation Magnitude

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Abstract

As a single-chip system with high integration, high performance, and low power consumption, Radio Frequency System-On-Chip (RFSOC) has broad application prospects in radio astronomy, particularly for telescope digital back-end systems. Radio telescopes impose extremely stringent electromagnetic compatibility requirements, and high-speed, high-frequency RFSOC operation generates severe radiated interference. To address the challenges of numerous interference sources and difficulty in quantifying radiation intensity across different sources, this paper proposes a radiation magnitude evaluation method at the component level to analyze the radiation intensity and impact of various components. Furthermore, electromagnetic radiation from RFSOC under different operating conditions is evaluated and analyzed at the board level. Based on the electromagnetic compatibility design requirements of telescopes, the electromagnetic protection requirements are analyzed to provide important technical support for further electromagnetic protection measures.

Key words telescopes: radio telescope, instrumentation: backend, methods: measurement and evaluation, techniques: EMC (Electromagnetic Compatibility)

1. Introduction

The digital back-end system serves as a critical component of radio telescopes, primarily responsible for signal digitization, processing, and data transmission. Due to process limitations, early astronomical back-end systems typically employed custom-designed Analog-to-Digital Converters (ADC/DAC) and Application-Specific Integrated Circuits (ASIC). Currently, ASICs have largely been replaced by Field Programmable Gate Arrays (FPGA), though FPGAs still require Central Processing Units (CPU) for control, with FPGA, ADC/DAC, and CPU devices remaining separate. Such discrete circuit systems are generally bulky, complex, and power-hungry, with costs and electrical performance often difficult to guarantee [1].

With continuous improvements in transistor process technology in recent years, many chips have reached transistor scales of hundreds of millions. The emergence of System-On-Chip (SOC) technology has integrated FPGA and CPU cores into a single chip, easily enabling programmable software control [2]. FPGA manufacturer Xilinx further integrated direct RF (Radio Frequency) sampling technology to replace discrete data converters, incorporating high-performance ADC/DAC into the SOC to produce RFSOC (Radio Frequency

System-On-Chip) [3], thereby consolidating all key functional devices required for radio astronomy back-end system design into a single package.

RFSOC simultaneously integrates high-performance ADC/DAC, CPU, FPGA, and ARM (Advanced RISC Machine) microprocessor resources [4]. The first-generation RFSOC achieves sampling speeds up to 5.0 Giga-samples per second (GSPS) at far less than 50%–75% of the power consumption and package size of discrete designs [2], with total ADC bandwidth reaching 16.4 GHz [5] and single-chip capability for up to 8 channels of 5.0 GSPS, 14-bit or 16 channels of 2.5 GSPS, 14-bit sampling.

The excellent performance and integration of RFSOC make it possible to implement complete radio astronomy receivers on a single board. Numerous astronomical research institutions are currently developing astronomical signal processing technologies based on RFSOC [6–10]. Liu et al. [2] evaluated the performance of data converters in the Xilinx ZU28DR RFSOC, utilized floating-point operations to capture data for offline analysis, and implemented a real-time integer-operation spectrometer on RFSOC, demonstrating that ADC performance is sufficient for radio astronomy applications. Steiner et al. [11] designed a broadband equalizer using the RFSOC platform for astronomical broadband phased array systems to address high-fidelity compensation technical challenges. Smith et al. [12] provided a method for running oversampled polyphase filter channelizers on SOC architectures without directly using hardware description languages.

The Qi Tai radio Telescope (QTT) [13–14] operates across a bandwidth of 150 MHz–115 GHz. The digital back-end signal acquisition and pre-processing system plans to adopt RFSOC for integrated development, with a sampling rate of 4.096 GSPS and quantization precision of 12 bits. The block diagram of the QTT digital back-end system is shown in [Figure 1: see original paper]. RFSOC is installed at the QTT prime focus and Gregorian focus, employing RF direct sampling technology to transmit data via optical fiber to high-performance computers for further processing (HPC: High Performance Computing, RF sig.: RF signal). However, electronic equipment near the QTT focal points must meet extremely high electromagnetic compatibility requirements [15], presenting technical challenges for RFSOC electromagnetic interference evaluation and protection design. This paper evaluates and analyzes RFSOC electromagnetic interference from both internal component and system-level perspectives to provide important technical support for further electromagnetic protection.

2. HTG-ZRF8 Development Board

To analyze RFSOC electromagnetic interference issues, this paper uses the HTG-ZRF8 development board currently employed in our laboratory as an example to examine its main components and potential electromagnetic compatibility problems. The HTG-ZRF8 development board utilizes the ZU28DR RFSOC chip, supporting 8 channels of 12-bit ADC (4 GSPS), 8 channels of 14-bit DAC (6.4 GSPS) ports, and high-performance front-panel miniature RF connectors for these ports. The board is equipped with 72-bit ECC DDR4 SODIMM slots providing up to 16 GB of memory with faster access speeds, while the processor supports up to 2 GB of DDR4 memory. The main components of the HTG-ZRF8 development board are shown in [Figure 2: see original paper]. Compared with general integrated circuits, the HTG-ZRF8 development board achieves functional diversification and performance leaps within a smaller volume, meaning the overall board structure and circuitry become more complex. Particularly, high-speed, high-frequency, and high-complexity board-level devices such as the ZU28DR chip carry high-speed signals rich in high-frequency components, which radiate or leak outward through gaps, oscillators, and equivalent antennas formed by potential circuit structures, generating strong electromagnetic radiation. Radio telescopes are complex systems comprising high-power drive subsystems for antennas, high-sensitivity receivers, data processing, data transmission, and control subsystems. RFSOC-generated electromagnetic radiation ultimately couples into these sensitive devices through various paths, subsequently causing serious impacts on system operation and astronomical observations.

To effectively analyze RFSOC electromagnetic compatibility, this paper conducts electromagnetic interference evaluation from two perspectives: internal components and board-level integration. At the internal component level, we evaluate and analyze component electromagnetic radiation magnitude, assess radiation intensity and impact of different components, and propose corresponding protection methods based on interference levels. At the board-level integration level, we evaluate and analyze electromagnetic radiation from RFSOC under different operating conditions and determine electromagnetic protection requirements based on telescope electromagnetic compatibility design specifications.

3. Evaluation of RFSOC Internal Component Electromagnetic Radiation

3.1 Radiation Emission Measurement and Analysis

To analyze electromagnetic interference from RFSOC internal components, near-field measurement methods are employed in an anechoic chamber to measure radiation emission characteristics of different modules. The test scheme schematic is shown in Figure 3: see original paper. The measured component radiation emission spectrum is recorded into array P using the following formula:

$$P = P(F[n]; V[n]); \quad (1)$$

where $F[n]$ represents frequency, $V[n]$ represents the power value corresponding to frequency points, and n is the number of measured frequency points.

With the RFSOC in the off state, the near-field probe is placed at the circuit center position, and the anechoic chamber environmental noise P_L is recorded through a signal analyzer, expressed in equation (2), where $V_L[n]$ is the power value corresponding to frequency points:

$$P_L = P_L(F[n]; V_L[n]).$$

3.2 Electromagnetic Radiation Magnitude Evaluation

Based on the above analysis, considering that component electromagnetic radiation spectra exist in two forms—broadband noise and narrowband signals—we propose to separate these two interference forms in the spectrum to evaluate their respective radiation magnitudes. For a given circuit board component radiation spectrum P and background noise spectrum P_L, the signal-noise separation threshold P_b is calculated based on the median $M[n]$ and standard deviation $A[n]$ of the spectrum as follows:

$$P_b = P_b(F[n]; V_b[n]) = P_b(F[n]; M[n] + 3A[n]);$$

where $V_b[n]$ is the array composed of circuit board component power values. The anechoic chamber environmental noise threshold P_B is:

$$P_B = P_B(F[n]; V_B[n]) = P_B(F[n]; M_L[n] + 3A_L[n]);$$

where $M_L[n]$ and $A_L[n]$ are the median and standard deviation of the environmental noise spectrum, respectively, and $V_B[n]$ is the array composed of environmental noise power values.

Based on the measured component radiation emission spectrum P, separation threshold P_b, and environmental noise spectrum P_B, broadband noise P_W and narrowband signal P_N are obtained by comparing V and V_b. For broadband noise $P_W(F[n]; V_W[n])$, $V_W[n]$ is the power value array of broadband noise, calculated using equations (5) and (6), where V_{Wn} is the power value corresponding to the n-th frequency point of the broadband noise spectrum, V_n is the power value corresponding to the n-th frequency point of the component emission spectrum, and V_{bn} is the power value corresponding to the n-th frequency point of the separation threshold:

$$V_W[n] = [V_{W1}\ V_{W2}\ \cdots\ V_{Wn}];$$

$$V_{Wn} = \begin{cases} V_{bn}, & V_n > V_{bn} \\ V_n, & V_n \le V_{bn} \end{cases}.$$

For narrowband signal $P_N(F[n]; V_N[n])$, $V_N[n]$ is the power value array of narrowband signals, calculated using equations (7) and (8), where V_{Nn} is the power value corresponding to the n-th frequency point of the narrowband signal spectrum, and V_{Bn} is the power value corresponding to the n-th frequency point of the environmental noise spectrum:

$$V_N[n] = [V_{N1}\ V_{N2}\ \cdots\ V_{Nn}];$$

$$V_{Nn} = \begin{cases} V_n, & V_n > V_{bn} \\ V_{Bn}, & V_n \leq V_{bn} \end{cases}.$$

The spectrum is only one manifestation of radiation. To further quantify radiation intensity, the Signal-to-Interference-plus-Noise Ratio (SINR) metric must be introduced. SINR is defined as the ratio of signal power amplitude to noise floor power amplitude, directly reflecting signal strength and commonly used to evaluate signal intensity. First, broadband noise SINR $\Delta V_W[n]$ is calculated. Since spectrum amplitude exists in logarithmic form, the SINR is calculated as:

$$\Delta V_W[n] = V_W[n] - V_{L1}[n] = [\Delta V_{W1}\ \Delta V_{W2}\ \cdots\ \Delta V_{Wn}];$$

where ΔV_{Wn} is the power value corresponding to the n-th frequency point.

In radiation interference magnitude evaluation, radiation intensity level increases progressively with SINR. Therefore, SINR factors must be assigned increasing weight coefficients based on magnitude, and their weighted average defines the broadband noise interference level $E_W[n]$ of electronic equipment. The weight y expression is given in equation (10), and the broadband noise interference level $E_W[n]$ expression is given in equation (11):

$$y = \alpha \Delta V;$$

$$E_W[n] = \left[\alpha V_{W1} \cdot \frac{\Delta V_{W1}}{(\alpha V_{Wn})}, \alpha V_{W2} \cdot \frac{\Delta V_{W2}}{(\alpha V_{Wn})}, \cdots, \alpha V_{Wn} \cdot \frac{\Delta V_{Wn}}{(\alpha V_{Wn})}\right];$$

where ΔV is the SINR of noise interference and α is an undetermined coefficient describing the mathematical relationship between SINR magnitude and noise interference. Larger interference SINR corresponds to greater intensity and shielding difficulty, thus carrying greater weight in electromagnetic radiation magnitude evaluation. To describe this relationship, based on engineering experience and statistical analysis of measured radiation emission data from electronic equipment in anechoic chambers, signals with SINR less than 5 dB are defined as weak signals with minimal impact; signals with SINR around 20 dB are defined as relatively weak signals; signals with SINR of 35 dB are defined as relatively strong signals; and signals with SINR of 50 dB are defined as extremely strong signals. Based on these statistical results, the expert scoring method is used to score interference signals, with signals having 50 dB SINR as the full score. The results are shown in .

Interference scores of noise with different signal-to-noise ratios

SINR/dB	score

The data from is fitted using equation (10), with results shown in [Figure 5: see original paper]. When $\alpha = 1.047$, the sum of squared errors of the fitted curve is minimized, yielding the best fit. Therefore, the broadband interference coefficient is determined as $\alpha = 1.047$.

In electromagnetic interference measurement and evaluation, numerous frequency point data typically exist. For data analysis simplicity and intuitiveness, broadband noise interference level $E_W[n]$ is divided into B frequency bands, each containing j frequency points:

$$n = B \times j;$$

$$E_W[n] = [E_{W1j}, E_{W2j}, \cdots, E_{WBj}].$$

The segmented form of broadband noise interference level $E_{ZW}[n]$ is then obtained by summing data within each frequency band:

$$E_{ZW}[n] = \left[\sum(E_{W1j}), \sum(E_{W2j}), \cdots, \sum(E_{WBj})\right].$$

After calculating broadband noise interference levels for all s electronic device electromagnetic radiations, the total broadband noise interference level matrix $W_W[s]$ can be expressed as:

$$W_W[s] = \begin{bmatrix} \sum(E_{ZW}[n])_1 \\ \sum(E_{ZW}[n])_2 \\ \vdots \\ \sum(E_{ZW}[n])_s \end{bmatrix}.$$

The calculation steps for narrowband signals are identical to those for broadband noise, differing only in the initial spectrum data, and are therefore not repeated here.

3.3 Case Evaluation and Analysis

For the Xilinx HTG-ZRF8 development board used in QTT, near-field measurement methods were employed using probes to measure radiation emission spectra of internal components across 30 MHz–1 GHz. The evaluation method proposed in Section 3.2 was applied to calculate broadband noise interference levels W_W and narrowband signal interference levels W_N for nine major interference components on the RFSOC, as shown in [Figure 6: see original paper]. In the figure, Band 1 spans 30–100 MHz, while other bands each have 100 MHz bandwidth.

[Figure 6: see original paper] shows that, in terms of frequency bands, both broadband noise and narrowband signal interference concentrate primarily in low frequencies (30–200 MHz), particularly narrowband signal interference, whose Band 1 (30–100 MHz) radiation interference magnitude far exceeds other bands. In terms of distribution, narrowband signal interference exists universally across all components, while broadband noise interference only exhibits high radiation magnitude in certain components. This occurs because most components on the RFSOC development board rely on clock chips for normal operation, and clock signals with their harmonics constitute primary sources of narrowband signals, resulting in narrowband radiation from all components. Broadband noise radiation magnitude is determined jointly by component power and internal structure.

Based on the component interference magnitude evaluation results in [Figure 6: see original paper], the key protection frequency band for RFSOC internal modules is below 500 MHz. The power management module (Component 1) and power regulator module (Component 2) exhibit high interference levels for both wideband and narrowband, followed by SD modules, memory modules, and IC chips. For board-level electromagnetic protection design, it is recommended to focus protection measures on these components, such as installing shielding covers or applying shielding materials to reduce the impact of modules with large radiation magnitudes.

4. Board-Level Electromagnetic Interference Evaluation and Analysis of RFSOC

For board-level electromagnetic interference evaluation, the overall radiation emission characteristics of RFSOC must be measured to assess their impact on astronomical observations and determine electromagnetic protection requirements. Radiation emission measurements were conducted in an anechoic chamber according to the GJB151B-2013 standard “Electromagnetic Emission and Susceptibility Requirements and Measurements for Military Equipment and Subsystems,” across 150 MHz–6 GHz. To improve measurement accuracy, both standby and program-loaded (normal operation) states were measured, with results shown in [Figure 7: see original paper]. Additionally, considering that RFSOC will be installed inside the QTT Gregorian focus and prime focus receiver cabins, interference level thresholds at these two focal positions were calculated following the electromagnetic compatibility control methods for large-aperture radio telescopes presented in literature [16]. Based on this, after deducting the 50 dB overall shielding effectiveness of the Gregorian focus and prime focus receiver cabins, the interference level limits for electronic equipment inside the two focal receiver cabins were calculated (shown as horizontal broken lines in [Figure 7: see original paper]).

[Figure 7: see original paper] shows that the radiation magnitude in normal operation state is slightly higher than in standby state, particularly noticeable in vertical polarization at high frequencies. For example, in the 5–6 GHz band with vertical polarization, the operating RFSOC board noise is significantly higher than in standby state, showing approximately 5 dB increase. RFSOC exhibits substantial noise interference in low-frequency bands, especially below 700 MHz, with maximum radiation exceeding the prime focus receiver cabin limit by 51 dB and the Gregorian focus receiver cabin limit by 22 dB. In the 1–6 GHz band, RFSOC interference is primarily narrowband, with overall noise slightly elevated, and maximum radiation exceeding the prime focus receiver cabin limit by 59 dB and the Gregorian focus receiver cabin limit by 63 dB. In summary, considering measurement uncertainty and interference margins, RFSOC installed in shielded receiver cabins requires electromagnetic shielding design greater than 70 dB to meet QTT electromagnetic compatibility control requirements.

Conclusion

This paper evaluates RFSOC electromagnetic radiation from both internal component and board-level integration perspectives. A component radiation magnitude calculation method is proposed to evaluate the electromagnetic radiation magnitude of RFSOC internal components, analyzing radiation intensity and impact of different components and proposing corresponding protection strategies based on interference levels. At the board-level integration perspective, electromagnetic radiation from RFSOC under different operating conditions is evaluated and analyzed, and electromagnetic protection requirements are determined based on telescope electromagnetic compatibility design specifications. This method can effectively evaluate RFSOC radiation interference and provides important technical support for electromagnetic protection of radio astronomy telescopes.

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Note: Figure translations are in progress. See original paper for figures.