Single-Event Transient Case Study for System-Level Radiation Effects Analysis

Michael J. Campola, *Member, IEEE*, Rebekah A. Austin, *Member, IEEE,*
Edward P. Wilcox, *Member, IEEE*, Hak S. Kim, Raymond L. Ladbury, *Member, IEEE*,
Kenneth A. LaBel, *Member, IEEE*, and Jonathan A. Pellish, *Member, IEEE*

***Abstract*— Analog single-event transient results are analyzed for two different applications within one system architecture. Application-specific analyses are presented on the MAX4595 commercial device using single-event effects criticality and goal structuring notation.**

***Index Terms*— Single-event effects, single-event transients, radiation, system-level effects.**

I. Introduction

Radiation-induced single-event transients (SETs) are a concern for microcircuit designs in the space environment. Naturally occurring particles that deposit charge within a device may cause device outputs or operations to fluctuate from expectations. The response can be amplified or extended by the devices' circuit application and may have system-level impacts. Common mitigation is that of passive filtering to dampen the response such that no downstream device tolerances are exceeded due to peak voltages, or to suppress the SET duration. In some applications the transient can affect the system's availability even if mitigations such as dampening or filtering are employed [1-3]. There also exist design implementations where mitigations like these cannot be used due to impacts on the performance of these systems (i.e., timing, impedance matching) [4, 5]. Previous studies report on methodologies to determine the type of testing best suited for applications and proactive hardness assurance for SET [6], [7]. This case study investigates SETs on two different analog switch applications where the addition of mitigation is in question, and the practicable use of results when the interruptions of functions are allowable.

Criticality and availability of the system design must be taken into account when determining mitigation approaches; therefore system-level descriptors such as a single-event effect criticality analysis (SEECA) can aid in determining impact to availability for systems in the space environment [8]. In order to verify that requirements have been addressed with respect to a specific application and architecture, goal structuring notation (GSN) can provide traceability [9]. Both criticality and availability are directly related to the reliability and maintainability in fault tolerant designs. Faults that propagate for system critical functions may hinder the desired availability of that system, mitigations seek to address the maintainability of that function, and how quickly the function can be restored after a fault [10].

The use of commercial off the shelf (COTS) piece-parts (i.e., individual ICs) or components (e.g., hybrids, stacked die, and card/box-level products) in space systems have the potential to insert new faults with respect to radiation effects, and may benefit from similar analyses when insufficient data exist to quantify the risk. Our case study may be extended to these more complicated applications in an effort to describe the reliability of a system. The example describes a device in two use-cases within one system, which has been analyzed using risk tolerance and system descriptors to weigh impact.

A single-event effect (SEE) evaluation was performed on the commercially available MAX4595 fabricated in Maxim Integrated's B8 process with a Si_3N_4/SiO_2 passivation and SiO_2 isolation dielectric [11, 12]. The device is a single-pole/single-throw (SPST) analog switch, with a single supply voltage (V+) and single CMOS/TTL compatible input (IN). The MAX4595 variant is configured to have its switched pins normally closed (NC/COM) unless there is a logic HI signal on the IN pin of the device. The analog switch has an internal resistance of 10Ω. The pinout of the device is shown in Fig. 1 with the corresponding labels. Normal device operation would allow for intentional control of the electrical connection between COM and NC.

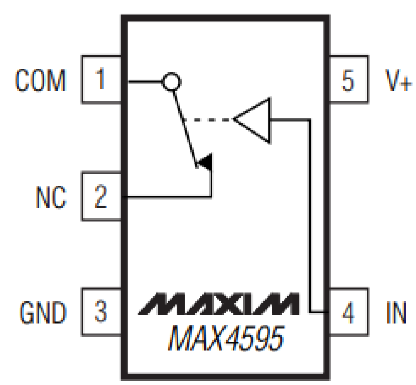


Fig. 1. Snapshot from the manufacturer's datasheet [11] of the device pinouts.

Manuscript received October 2, 2020. This work was supported in part by the NASA Electronic Part and Packaging Program (NEPP) and NASA Flight Projects.

M. Campola, R. Austin, E. Wilcox, R. Ladbury, and J. Pellish are with NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA (email: Michael.J.Campola@nasa.gov).

H. Kim and K. LaBel are with SSAI, Inc. work performed for NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA, (email: Kenneth.A.LaBel@nasa.gov).

Non-destructive SEEs may not pose a hazard to the device or exceed its operating limitations, but are still capable of interrupting a *system-level* function. A transient pulse may alter the value of averaged measurements, or cause disruption to reference voltages. As a case study, this part and its applications are used to illustrate the benefits of using SEECA or GSN to describe and track the impact of radiation effects, such as SETs and their mitigation in a system rather than just considering the worst-case. The following information serves an example of the role that these tools serve.

II. Application description

As with most spacecraft, the size, weight and power (SWaP) of a COTS solution make it an attractive replacement over the radiation-hardened or military equivalent piece-part solutions. The desired design trades for capability can be driven by any one parameter, including, but not limited to the lead-time of ordering such parts, lower power, or faster clock speeds. The package size played a role in the case described – a single switch for use within focal plane electronics that needed to fit within a camera's enclosure, resulting in constrained printed wiring board space.

This particular card contained the MAX4595 utilized in two different ways, and was replicated for a number of signal chains. The first application (I) controls power distribution to an amplifier circuit that controls desired buffering of the video signal. The analog switch therefore controls throughput by disconnecting the NC contact, controlling the sub-circuit's 5 V supply. The second application (II) is in-line with the video signal itself, selecting one signal chain to pass to the buffers, but cannot utilize filtering because of timing constraints. Fig. 2 simplifies the two applications that would be running simultaneously on a single card to a block diagram. These two applications pose different *part-level* sensitivities to SET–

1) Interruption on the power supply to the video signal amplifiers – sensitivity to transient duration. If the SET is long enough in duration the power to the amplifiers will be removed which changes the amplifier output and could effectively turn the amplification off.
2) Disruptions on the transmission of the video signal output–sensitivity to transient peak values. If the peak-to-peak values are outside of the expected output range at a high rate, the average measurements would change, disrupting science data.

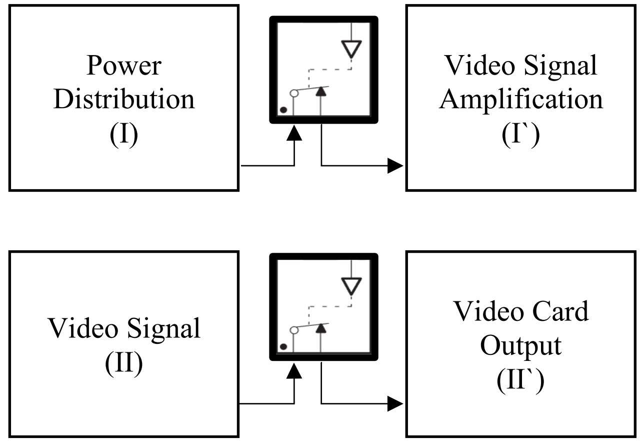


Fig. 2. Application block diagrams. Two simplified use-cases of a commercial switch that have the potential to propagate SET responses at a system level if un-mitigated. The applications shown are later referred to as the power (I) and video (II) chains, where a primed notation denotes that perturbed device operations due to SET has the potential to impact the system.

III. data Collection

The devices under test are listed in Table I, including their package markings and some additional information. The small package size provided limited information and most information comes from the manufacturer datasheet [11], [12]. The potential single-event latchup (SEL) vulnerability that exists in commercial CMOS, and lack of available test data drove the need for SEE characterization.

Table I
Device information

Part Information	Value
Number:	MAX4595
Manufacturer:	Texas Instruments
Additional Case Markings:	6SB
Quantity Tested:	3
Function:	SPST
Technology:	CMOS (B8)
Package Style:	SOT-23

Decapsulation was necessary in order for the heavy-ion beam to access the active region of the silicon chip with sufficient range. Fig. 3 shows the prepared device under test (DUT) before and after decapsulation, as well as in line with the cyclotron beam during testing. Fig. 4 depicts a block diagram of the test setup used to capture data during the irradiations. This information and more is reproduced with added detail on ion species and facility information in the publicly available test report [13]. The test campaign had a priority to characterize destructive SEEs, but found no susceptibility. However, transients were recorded in the intended application conditions.

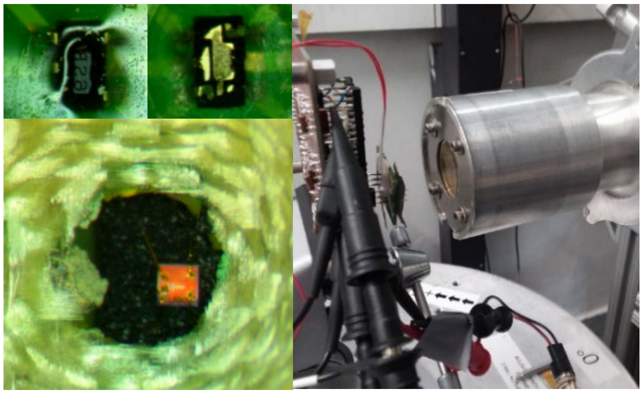


Fig. 3. Device prepared for heavy ion testing (left) and in line with cyclotron beam (right)

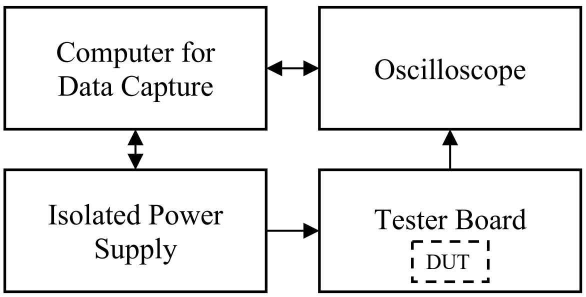


Fig. 4. Test setup block diagram for data capture remotely at test facility

During the test, the oscilloscope captured SET waveforms when the output deviated from nominal voltage ranges. Fig. 5 shows the SETs on the NC output of the device. We observed that the response of this application under test was a negative-going transient that varies in amplitude and duration. An input voltage was applied to one terminal of the switch, while the other side was monitored. Smaller transients may have gone unrecorded if they were below the oscilloscope trigger settings. The negative going characteristic is likely to be the result of the control logic for the switch being hit, causing a momentary disconnect of the switched terminals.

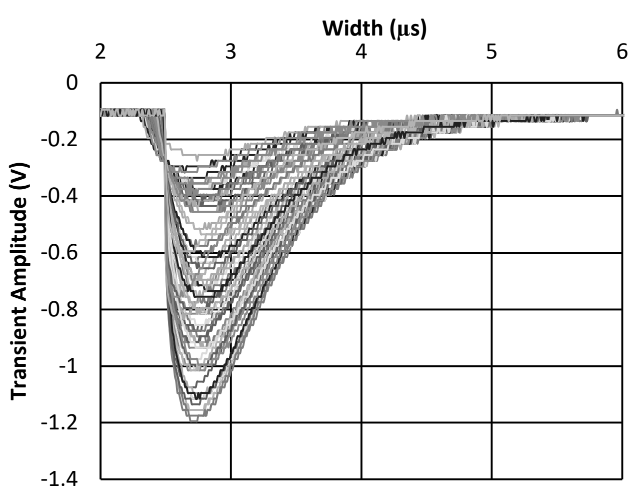


Fig. 5. Unfiltered response of the MAX4595 to heavy ions during a single run with Au ions, at a single LET.

Collection of transient data from ground-based heavy-ion facilities is used to construct the cross-section versus. LET for a particular device in a particular application, as shown in Fig. 6. There are data at four LET points overlaid with a Weibull fit to those data. This is by no means a full characterization of the transient events on the device, but was recorded while testing for destructive SEEs. The results are nonetheless useful for the case study. The SETs on the device in a NC state with 5 V on one side of the switch were recorded for only two of the three ion species, and only became sizeable (> 0.2 V) with LET > 50 MeV·cm^2/mg. The cross-section then may be used to estimate rates for a given environment.

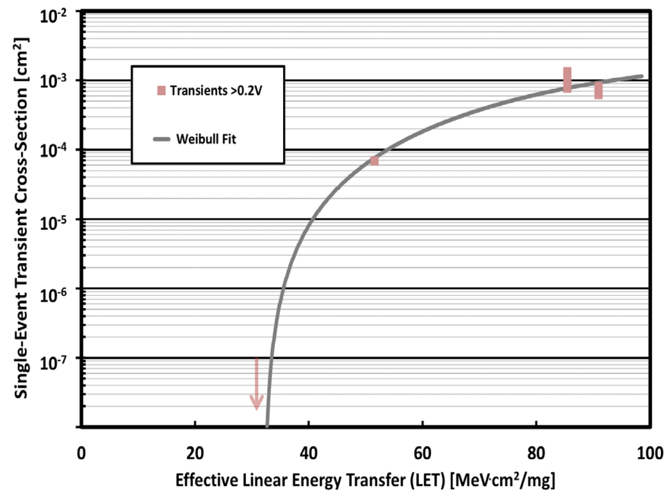


Fig. 6. Cross-section of MAX4595 single-event transients with magnitude greater than 0.2 V, downward arrow used to show LET value where no SET were recorded to a fluence of $1\text{x}10^7$ ions/cm^2.

IV. Analysis

Guidance on the number of events to record for a given fluence of particles are given in JESD57A [14]. Collection of sufficient numbers of transients for each experimental condition (LET, bias, temperature, etc.) allow for statistical inference into the results. Attention to the distribution of results rather than the counts prevents implicitly biased analysis if multiple runs with the same conditions are repeated more than others.

To communicate many results from SET testing with multiple ion species, angles, and energies which result in varied charge depositions, the pulse width (PW) and pulse height (PH) were extracted for all captured transients. Fig. 7 illustrates the PWPH with histograms for the ordinates on the same plot. This visually identifies the transient shapes and trends that were most prevalent during ground-based testing. The benefits of this type of response analysis were discussed in earlier publications [3], [4], [15].

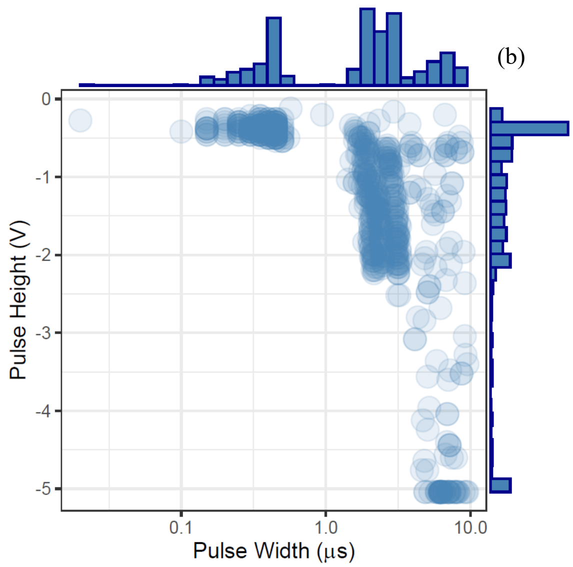
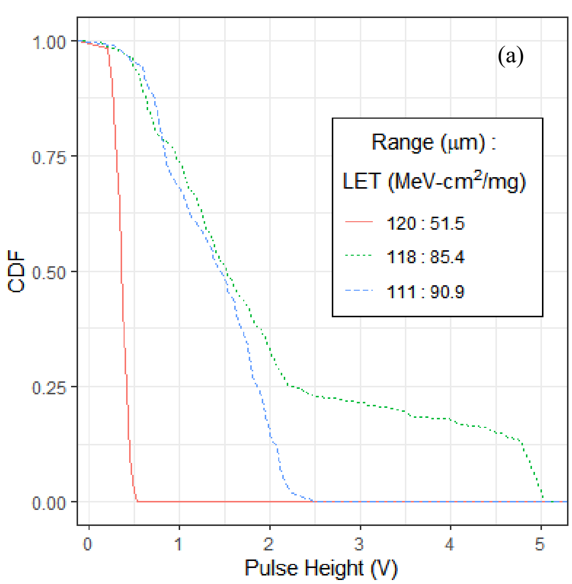


Fig. 7. Pulse width and pulse height of all recorded transients during SET testing with the histograms capturing the event counts plotted on the outside of the ordinates.

Binning helps us to look at how the data are distributed. Fig. 7 shows how the increased PH and PW are correlated, though there are gaps in the dataset. We can also see a large count at a PH of -5 V suggesting that the supply rail and ground are limiting the response.

In addition, binning the data can be used to create an empirical cumulative distribution function (CDF). Fig. 8 helps us to visualize the aggregated dataset for percentages that are greater than a given parameter of interest. Noting that probabilities of the PH and width exceeding x decrease rapidly suggest that more than a quarter of the recorded transients were greater than 5 µs and more than a quarter had PH greater than 2 V. Though this is not a full characterization of SETs on the device, this limited dataset is enough to analyze the system for impacts, when considering the functional applications.



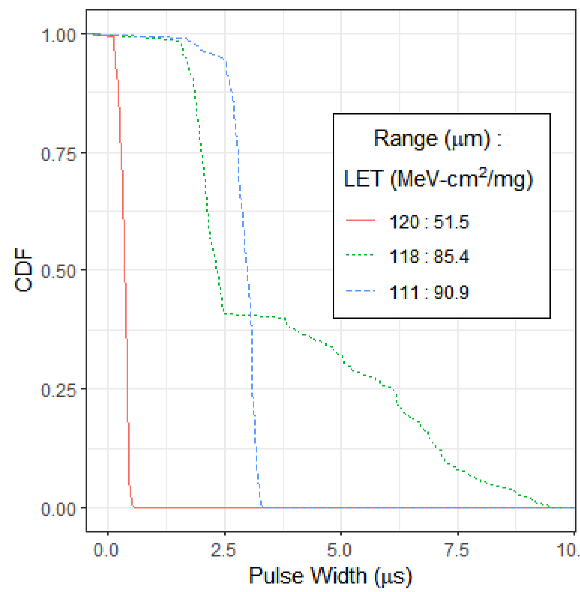


Fig. 8. Reverse empirical CDF for pulse height (a) and pulse width (b) of recorded transients during heavy-ion testing. The largest recorded pulses were from Au ions at normal incidence, suggesting that range may have been insufficient for angled results at the highest LET.

Despite the nuances within the dataset, the recognition that the device has the ability to interrupt the switch operation for varied durations that exceed allowable design limitations requires further analysis. In order to determine *system-level* consequences, including criticality and likelihood, we must link radiation requirements to broader mission success criteria. Taking the specific part/component response into account, the objective will remain to determine whether or not requirements are being met in the design. Two methodologies of gathering and answering that question are described in the following sections.

A. Single-Event Effect Criticality Analysis (SEECA)

SEECA does not just capture a system-level assessment of SEE response at the part level, but it also utilizes those concerns to identify and categorize impact to the system in question [8]. The characterization of the device response to heavy-ions provides the part level susceptibility to begin SEECA at the circuit level.

SEECA calls for compartmentalization of impacts that SEE piece-part responses, and the propagation of that response, can have. These "criticality classes" or categorizations are unique in that they capture the consequence of unintended operation at the system-level.

1) *Error-Critical* – function where SEE are unacceptable.
2) *Error-Vulnerable* – function where low probability for SEE is required, response with mitigation or risk of SEE is permissible.
3) *Error-Functional* – function may be unaffected by SEE (possibly by error-corrections scheme, mitigation, or redundancy), large probability of events may be acceptable.

Conducting a severity assessment for each of the device applications and functions yields that the power distribution chain (I) is *Error-Vulnerable* while the video signal chain (II) is *Error-Functional.* Table II aligns the use case and the concerns or constraints where the "primed" label refers to the output of the switched applications.

TABLE II
SEECA SUMMARY

Use Case	Mission Concern/ Constraint	SEE Severity Assessment
Power to Amplifiers (I)	Duration of transient cannot cut power to amplifiers during measurement, rate cannot exceed 1 every 30 minutes (I`)	Error-Vulnerable
Video Signal Chain (II)	Rate cannot exceed 1 every 120 seconds, duration cannot exceed 1 second for integration/ averaging (II`)	Error-Functional

In these use cases, the severity is tied to the two different functions explained in the application description, but there is additional context in terms of PW for use-case I. Here we give values for the threshold to which the system will be impacted by the SETs.

1) A pulse width greater than 5 microseconds will cause power off condition, some transients recorded were greater. Availability required is 30 minutes.
2) Transient amplitudes greater than an absolute value of 1 V during integration would be sufficient to invalidate the science measurement, some transients recorded exceeded that limitation. Availability required is 120 seconds.

For use case I, the *function's* availability requires that the SET rate would need to be less than 4.8 x10^{-1} /device/day and for use-case II and the rate would need to be less than 7.2x10^{3} /device/day. In addition, the knowledge that the camera subsystem use is only during the longest mission phase, imaging operations, provides context for which environment model is applicable when estimating the rate: near-earth interplanetary (NEI) / geostationary (GEO) flux transported through 100 mils Al was selected from CRÈME for calculating the estimated rate based on the intended mission's orbit and typical shielding amount [16]. NEI/GEO environment was considered nominal, while the October 1989 worst day was used to approximate rates in the event of increased solar activity. Table III shows the Weibull fit parameters and corresponding SET rate estimations for those two environmental conditions.

TABLE III
SET RATE SUMMARY

Weibull Fit Parameters	Environment	Estimated Rate (transients /device/day)
LET threshold = 32.1 MeV·cm^2/mg Limiting Cross-Section = 2 x 10^{-3} cm^2	NEI/GEO	1.55 x 10^{-4}
Shape = 2.5 Width =71	*October 1989 Worst Day*	*4.80 x 10^{-1}*

The calculations are of how often the system will see an SET similar to what was recorded when testing for the two environmental cases. Due to the high onset LET, the outcomes depict low event rates (or likelihoods during the error-vulnerable operations) when compared to the availability, which can be used to verify requirements. Note that a solar particle event on the order of the October 1989 worst day would be sufficient to cause an interruption to power chain (I) if all transients were >5 µs. SEECA categorizations of the SEE severity at the functional level paired with rates of SET predicted at the part level allow for the distinction that use-cases would not be interrupted.

B. *Goal Structuring Notation (GSN)*

GSN provides a framework for capturing requirements and the argument for their verification. GSN is a visual argument that the system operates correctly, in this case, within the specified radiation environment. Fig. 9 shows a generic assurance case using GSN. The top goal is a stated mission requirement, the context gives supporting information or background on the radiation environment. The strategies are the inference into what is necessary to achieve that goal, and the justification provides the rationale. Any unsubstantiated claim is tracked as an assumption. Finally, the solution is the evidence. Documentation on GSN defining the colors/shapes that denote the functions can be found in the public domain [9].

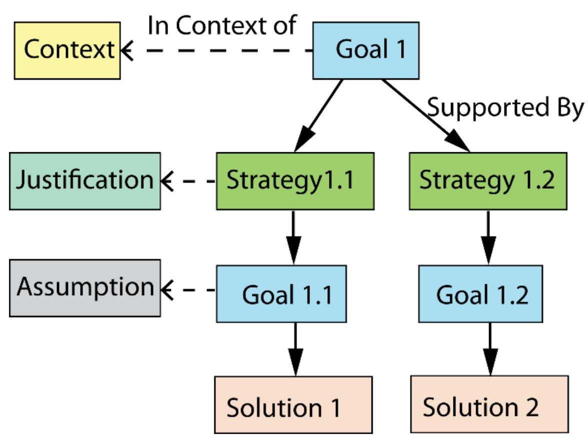


Fig. 9. Generic GSN graphical argument for an assurance case [9].

For the use case of the MAX4595, though the fundamental goal may be more generic, we can start our GSN with a top goal of the mission's operational availability (A_O) requirement [17], providing context of the radiation environment that has been modeled. We can call out the use of and analysis such as SEECA, and leverage test results. The visual argument can be seen in Fig. 10.

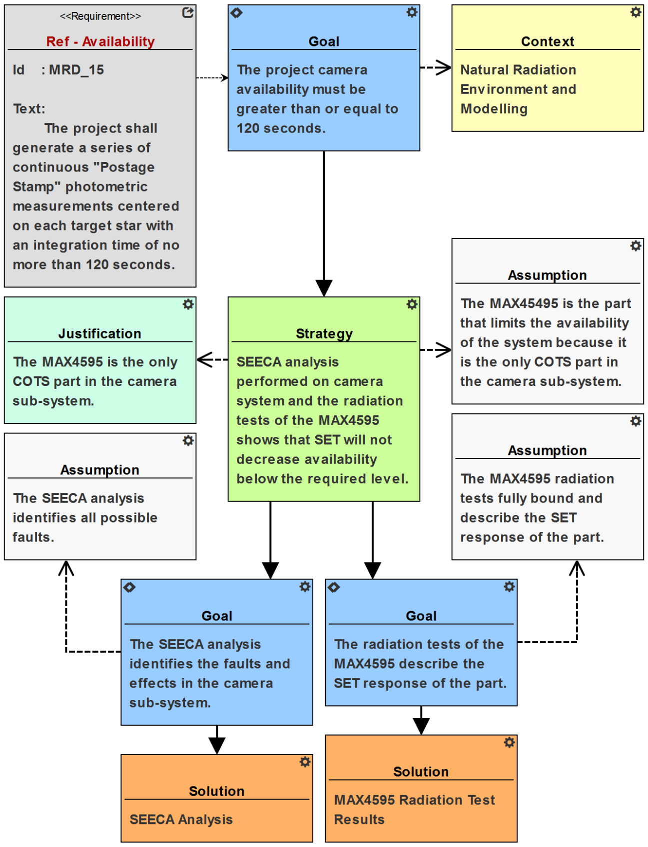


Fig. 10. GSN argument for meeting the availability requirement of the camera. The graphical argument captured only addresses the MAX4595 SET assurance case.

The power of using GSN comes with being able to track the reasoning behind justifications and supporting data. Additionally, cross-linkages between requirements, strategies, assumptions and solutions can also be tracked and linked to models of the system. These types of analyses can be extended through a thorough model-based mission assurance (MBMA) approach with tools, such as SEAM [18], [19]. In our example, the mission requirements flowed to the MAX4595 were met through confirming the availability constraint at the subsystem level from a SEECA, requirements verification was confirmed and tracked through a visual argument in GSN.

V. Conclusion

The results of SEE testing on the MAX4595 were application specific and show the device susceptibility to SETs. The worst case SET PW and PH that were recorded have potential impacts to the different system functions. Specifically, transients with a PW greater than 5 µs and/or amplitudes greater than 1 V were recorded during testing. These test outcomes were determined to be acceptable for use after performing a SEECA analysis to determine the how the availability requirement for the COTS camera would be impacted by transients in the MAX4595. The argument for the correctness of the analysis and applicability of the test data was captured using GSN to facilitate review of the COTS camera availability requirement.

A system-level analysis can allow for the use of COTS parts in spaceflight missions that exhibit non-destructive SEE if used to capture and verify radiation requirements. In some use cases where there are limited data or lack thereof, functional operation of the device in systems with mitigation, or in non-critical applications can be justified; in order to do so, documentation of assumptions and rationale are paramount. The limited dataset obtained on SET while heavy ion testing the MAX4595 was analyzed against the availability requirements for two applications with different SET sensitivities.

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