NIRCam Systems Engineering: The Recipe

Bruce Steakley, Lockheed Martin Advanced Technology Center, 3170 Porter Drive, Palo Alto, California, USA

ABSTRACT

NIRCam is a highly sensitive, multi-spectral, high-resolution, cryogenic, compact, light-weight, and rugged near infra-red camera on the James Webb Space Telescope. The successful development of NIRCam is aided by good system engineering practice. This is a discussion of important elements of NIRCam System Engineering with some light-hearted contrast to a more common activity.

1. INTRODUCTION

Is there a recipe for good systems engineering process? Isn't there a set of rules that we can follow to better ensure project success? Can we get a plan that applies to our unique project? I'd like to say yes, yes, and yes. Here are two projects. There is a significant difference in value, complexity, and technology. However, they share a few remarkably similar systems engineering features. One is a state-of-the-art space-borne astronomy camera and the other is a culinary (albeit high calorie) delight. We'll provide background to answer these questions by discussing the development of these two products and highlighting important steps along the way.

1.1 The Near-Infrared Camera (NIRCam) project

Where do we start? Define the mission and the product. NIRCam is an astronomy camera that will take pictures and support the NASA Origins program. Identifying Mission Objectives provides the foundation for determination of lower level requirements. The first objective is the detection of first-light objects. Another objective is to gather data to aid in the explanation of how galaxies are formed. A third objective is to detect new planets. Detecting dim first-light sources drives a critical requirement to provide the highest possible sensitivity. Considerations for how large to size the field of view are important to size the search field to cover enough sky in a timely manner. We'll need a filter set capable of provide adequate spectroscopy and a stable instrument for high quality photometry to identify a reasonable set of galaxies in a deep multi-color survey. Studying galaxy formation drives spatial resolution that is small enough to distinguish galaxy shapes We work to understand and flow-down these drivers early in development. Good product definition provides for more efficient development and assignment of roles and responsibilities. Care must be taken to make sure that all product components and features are defined to enable development of a complete system of optics, mechanical elements, mechanisms, electronics, thermal, and software.

• **Detect first light**
• **Provide spectrally and spatially resolved images to investigate galaxy formation**
• **Provide a coronagraph capability to look for new planets**

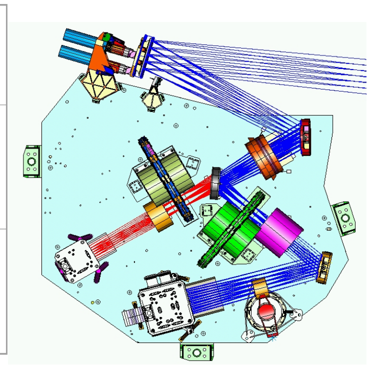


Figure 1: Systems Engineering Begins with Mission and Product Definition

1.2 The lasagna fine dining experience

Where do we start? Here it is also important to define the mission and the product. The mission here is very simple. It is to create an enjoyable and memorable classic Italian dinner. The product is a pasta and meat or vegetarian casserole. The mission implies something more than giving your guests something to eat. Just as NIRCam is only one element of the larger JWST mission, the Lasagna entrée is one element of the larger fine dining experience. For today, we will limit our discussion to the Lasagna and save wine pairing and side dishes for another discussion.

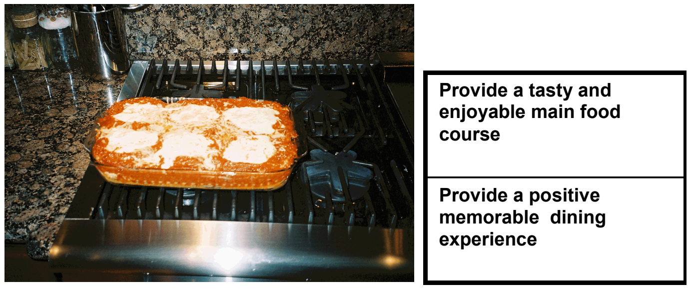


Figure 2: Define the Mission and the Product

2. SYSTEMS ENGINEERING AND PRELIMINARY DESIGN

2.1 Systems Engineering on NIRCam

It is important to design or layout Systems Engineering tasks in context with product design and development needs. A good systems engineering program needs to not only support customer inquiries but support the design teams hardware and software development needs. On complex large instrument projects like NIRCam, there are three critical phases on the road to completing a detailed design. These events consist of a System Requirements phase, a Preliminary Design phase, and a Critical Design phase. The scope of this paper will take us only partway, however, through a significant portion, the Preliminary Design phase.

Why three early phases and reviews? This is due to the complexity of instrument development and the level of coordination and agreement needed along the way. Before committing considerable resources to design work, it is important to understand the system requirements. With a good set of mission or science objectives there is still the task of translating these into well-defined product requirements. Requirements that quantify how well the instrument must work, how the instrument will be operated throughout its life, the mechanical, thermal, and radiation environment within which the instrument will be operate, and the launch environment the instrument must survive. There are also very important scarce resource requirements such as limits on mass and power driven by booster and spacecraft capabilities. In order to judge the viability of implementing such requirements, it is necessary to define a design concept and architecture. Identification of functional and physical interfaces between major elements are needed to establish a viable architecture.

The combination of these requirements, architecture, and concept definition provide a departure point for the preliminary design. The System Requirements phase will produce a good set of system product level requirements. The preliminary design phase decomposes system requirements into lower level subsystem requirements and develops system and subsystem preliminary designs. The Preliminary Design Review (PDR) is an event to make the case that the preliminary design satisfies all system requirements with acceptable risk. It is a gate for the customer and stakeholders to approve the design and authorize proceeding with the significant effort of detail design. It also provides an event for approval and authorization to proceed with development of costly but necessary engineering development units. Heritage and legacy programs can provide confidence-building examples, however, the drive to make new discoveries will push performance levels beyond what has been accomplished before. High fidelity prototype hardware and engineering units are a necessary interim risk reduction step. We need to practice and refine before proceeding with the flight system. The Critical Design phase includes detailed design of all components and culminates in a review to assess compliance with requirements and authorization to proceed with fabrication of flight hardware. The general nature of systems engineering tasks is to define and maintain requirements, operations, interfaces, system trades, system models, specialty engineering and verification.

2.1.1 The Lasagna Fine Dining Experience planning phase

Even relatively simple efforts like preparing a Lasagna dinner are best tackled with some level of planning. It is important to consider the nature of the occasion and not just a headcount. Some events are formal while others are not. An estimate of the number of adults and number of children will also help guide the number and size of servings. It is important to know if you have any vegetarian or other special needs. Today, we are going to assume the event is a school graduation with a total of eight guests, no vegetarians, and a mix of adults and a few kids. Once you have selected the diner date, this is a meal that can be prepared and served the same day, or prepared the day before, refrigerated and reheated with equal success. To avoid those anxious cooking moments, consider the timeline in advance and give yourself some schedule margin. Quality is also a consideration. Today, we have all four grandparents attending so the quality needs to be impeccable. If my college buddies were coming over, it would be different. One can imagine how awkward it could be to start cooking with no thought about these considerations first.

3. SYSTEM REQUIREMENT DEFINITION

3.1 Requirements hierarchy

After the mission requirements and product concept have been agreed upon, it is time to define the system requirements. This is a process that first focuses on identifying driving requirements and establishing the hierarchy of requirements. Driving requirements are those that dictate critical technology needs or major architectural considerations. These requirements may come from various sources. These include science requirements, operational considerations, mission life, scarce observatory platform resources and interfaces, mission assurance or quality requirements. During this development, it is important to capture agreements in controlled documentation. The requirements hierarchy figure below shows the documentation and hierarchy established at the end of the NIRCam System Requirements Phase. The JWST parent requirements to the NIRCam Specification (or NIRCam Functional Requirements at the time of SRR) are captured in the five top row major documents shown in figure 3. Identification of ownership is important. Ownership includes establishing a good understanding, documentation, and maintenance throughout the project life. Requirement responsibility and management might lie with many organizations, companies, and government groups, making the necessity for clarity in ownership all that more important. This will help identify who is needed to address and resolve issues and or make changes as the program evolves. This is critical to all Aerospace programs but not so much for our simple Lasagna example.

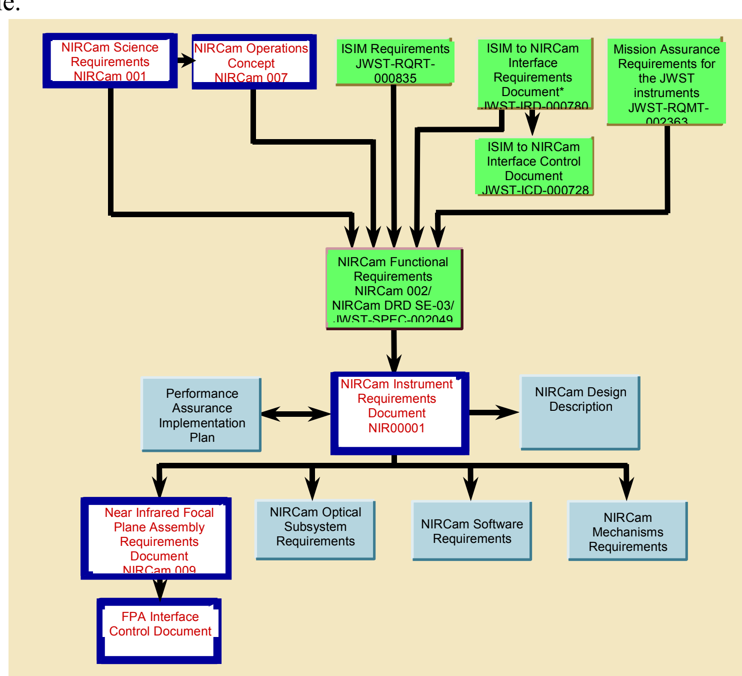


Figure 3: Requirements Hierarchy

3.2 Requirements flow-down and allocation

Requirements definition and understanding is essential. This includes identification of what is important and writing it down. Here again, coordination with the Principal Investigator and customer is important. During the process of attaining agreement, it is good to document the rationale or basis. This should include a description of what the driving parent requirement is and where it can be found. NIRCam's objective of detecting first light implies considerable attention to radiometric sensitivity. Part of the above understanding involves evaluation of component dependencies and performance expectations of enabling technologies. Figure 4 below illustrates a systems engineering perspective as it applies to the task of decomposing sensitivity.

The requirements allocation tool, provided by Marcia Rieke, captures the relevant mathematical relationships and is called the NIRCam Sensitivity Spreadsheet (ref. 1). This tool has proven heritage in predicting performance of the MIPS instrument successfully taking pictures and data on the Spitzer observatory. There are assumptions that make up the boundary conditions for determination of NIRCam performance. This includes the sky background and JWST Optical Telescope Element (OTE) parameters. These include such values as the zodiacal radiance, the telescope 6.5m diameter, and the OTE point spread function. NIRCam can't change these. Our NIRCam science instrument contributes its own optical transmission losses, spectral transmission profiles, and magnification or pixel scale. These NIRCam values can be traded for best performance given available and affordable technology. The HgCdTe detector signal and noise contributions are in the form of dark current, read noise, and quantum efficiency. Operational considerations are driven by integration time to achieve the required signal-to-noise ratio (SNR) for reliable detection. Some lower level requirements are allocated from top down considerations and others are established by the limits of the best available technology. This enables early requirements allocation as well as performance predictions to be made during the development of NIRCam.

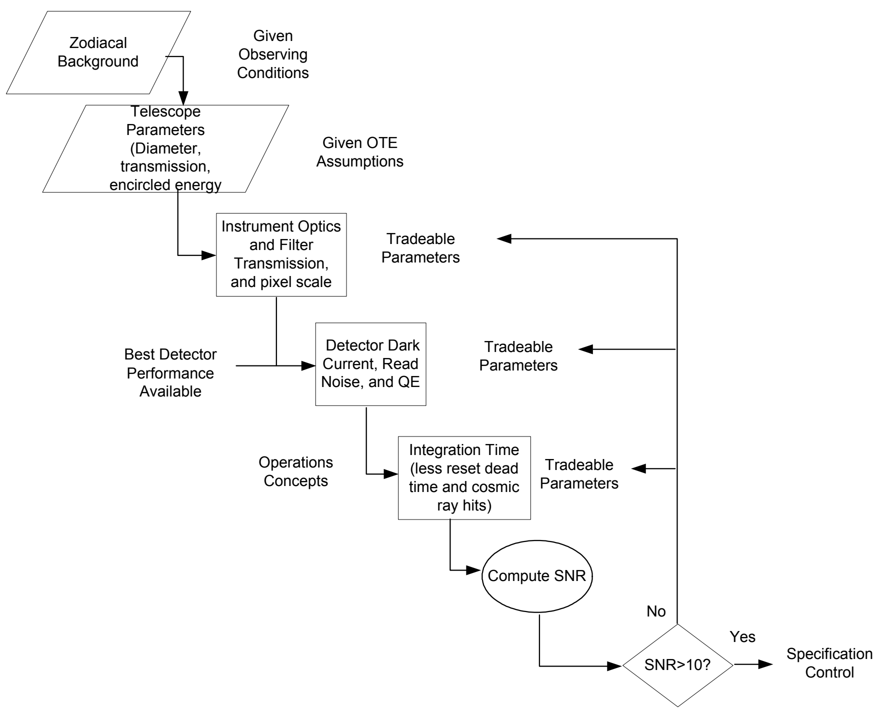


Figure 4: Example Allocation Structure: Sensitivity Requirements

Broad considerations are needed for NIRCam design, fabrication, integration, test, launch, deployment, and operations. For each of these various development and operational stages, requirements assessment is needed for optical, mechanical, thermal, electrical, and software. These requirements will also span the specialty engineering and quality aspects of electromagnetic effects, contamination control, reliability, materials and process, safety, and product assurance. Early in the development there may be a perception that some requirements might be more important than others, such as those that are directly linked to top level mission objectives. However, there is a large family of requirements necessary for a system to be developed, function in its mission environment, and last a mission lifetime. Failure to comply with anyone of these at the system level may force a switch to a redundant side, degraded performance, or even the loss of a mission. In that sense, these are many equally important requirements.

3.2.1 The Lasagna recipe

We need to size the ingredients based upon the number of guests. We are planning to entertain eight and given prior experience and lessons learned, we will go with a 9 x 13 inch pan. First brown the beef over high heat. Combine with tomato sauce, paste, and spaghetti sauce and simmer on low for 20 minutes. Boil the noodles, drain, and lay three side by side in the bottom of the pan. Add a layer of meat sauce. Slice the mozzarella cheese into approximately 18 thin slices. Place 6 of these evenly spaced on top of each meat sauce layer. Add about 1 tablespoon of Ricotta cheese on top of each mozzarella slice for each layer. Repeat this noodle, meat sauce, mozzarella, ricotta cheese major layer 3 times. Sprinkle parmesan cheese evenly over the top of the final layer. Cover and place in pre-heated 375°F oven and bake for 40 minutes. Remove cover and verify cheese is beginning to bubble. Continue to bake uncovered for about 5 more minutes to brown top layer. Remove from oven and allow to cool. Sprinkle parmesan cheese on top and serve warm.

Ingredients	Quantity
Ground Beef, Lean	1.75 lbs.
Tomato sauce	15 oz
Tomato paste	24 oz.
Spaghetti sauce with mushrooms	3 cups
Extra Wide Lasagna noodles	~ 10 noodles
Mozarella cheese	16 oz.
Ricotta cheese	15 oz.
Parmesan cheese	6 oz.

Figure 5: Lasagna Ingredients

3,3 Trades

Conducting trades early in a program is very beneficial. It is very rarely clear what the best design choices are so spending some time evaluating various options and alternatives is appropriate. This may improve performance or provide acceptable performance at more affordable cost or earlier schedule. In addition, development of state-of-the-art near-infrared cameras has some finite risk so this is a consideration. There are various decision making aids to facilitate trades that range from brainstorming, to Kepner-Trego analysis of weighted scoring of issues, to application of Six-Sigma techniques. Perform these trades in an objective and timely manor. Trades that take months and years are extremely costly to large projects and often are not needed to allow a reasonable choice of which path or option to choose. Trades that take weeks can be more readily injected into the normal cycle of project development. NIRCam conducted such trades as comparing refractive vs reflective vs hybrid optical configurations, alternatives in refractive optical materials, and options for structural material and configuration. We'll revisit trades in the upcoming preliminary design phase.

3.3.1 Lasagna trades

What possibly could be traded in preparing Lasagna? Well as a college student, we barely had time to eat, let alone cook. There was a big consideration on how much time this took. There is a step for separately boiling the noodles. Could it be made without boiling the noodles first and proceed straight to baking? I have studied this by trying both methods. These methods were a wash regarding the cost of the ingredients. It took 20 minutes less by not boiling the noodles first, however I could really taste the difference. In school, the value of a fast schedule was more important to me so the approach that went straight to baking came out on top. However, now I value the taste and texture much more and always boil the noodles first. I have also traded various spaghetti sauces that have included onions, garlic, pork sausage and assorted seasonings and have found recently the ready-made spaghetti sauces with mushroom from various producers to be quite good. Personal taste and experimentation are appropriate. I like a strong tomato flavor and have kept tomato sauce and paste in addition to the spaghetti sauce. Make-or-buy decisions may include make from scratch or buy ready to integrate.

3.4 Margin management

Mass and power are two of the most visible limited resources on spacecraft. Know your requirement…and know your performance prediction. The performance or capability prediction is based upon the actual product design features, component technologies, and the operations concept. The requirement is most likely an allocation from above. It is not sufficient to simply know one or the other. The difference is your margin and it is the magnitude of positive margin that is an indication of the system robustness. Fragile systems on the edge of performance compliance may fail or disappoint more often than not. Too much margin is expensive to carry so more and more is not necessarily better. Establish a good margin assessment early and update it frequently. Contingency is a term that means something entirely different. Mass performance predictions are supposed to be appropriate at the time of launch. There is a component that can be evaluated as of the current status with the current models and analysis. There is also a component that is a project ahead to the end of development and launch. Our company has been building payloads for many years and keeps track of historical growth. This is the growth throughout the stages of program development. This growth has occurred even when managed and is a natural consequence of the aerospace development process of ever-increasing design detail adding mass. During the early concept phase, the contingency is relatively high, during the critical design phase it drops, and at time of final acceptance test is even lower. This contingency is added to the basic estimate. The nominal expectation is that the basic estimate increases with each phase, the contingency is decreasing and the sum of the two provides a most probable estimate at launch. It is important to check with your own company for their own records and guidelines on how to establish the magnitude and timing of the application of this contingency. This concept of margin management is most rigorously applied to mass and power.

3.4.1 Lasagna margin management

It can be very embarrassing to run out of food at a dinner party. It is also can be unclear as to how many people will be coming over or how much each of them will eat. Over the years, I have learned that a 9x13 will probably serve 7 very hungry people and typically 8 or even 9. I still estimate ingredients for at least one more than I expect. I also have learned that reheated Lasagna is still very tasty so I don't worry about having 'leftovers.'

3.5 Tools and models

As a part of requirements allocation and performance prediction, it is good to use well-understood math models, tools, and keep a record of parameters in reliable data bases. These might be commercial products or tools developed on company money which carry proprietary limitations. The tools need to have a proven heritage on other programs or applications. The figure below shows some of the various tools NIRCam employed early in the system requirements phase. These models and tools will also be used throughout the program with ever increasing fidelity and level of validation. Model predictions will be validated by comparison and correlation with measurements. Use of well-understood and commonly available tools also facilitates the exchange of high-fidelity models between organizations. This enhances the integration quality between the various organizations separately developing hardware and software in parallel, which will also someday all perform together on the JWST observatory.

Table 1: Example of Various NIRCam Math Models

Model / Data Base	Usage
Code V from Optical Research Associates	Optical design, performance assessment, sensitivity analysis, requirements compliance
Zemax	Optical design, Sensitivity Analysis
Data Base : Optical Material Properties	Design reference material, Capture published and measured properties
SDRC I-DEAS	Optical/Mechanical solid model layout and design. Preliminary Finite Element modeling. Some static stress and some modal
MSC/Nastran	Structural Verification and GSFC deliveries. For transient or frequency response analysis, the NASTRAN model is run through Lockheed Martin DMAP (Direct Matrix Abstraction Program). Some static stress, some modal
Thermal Model Generator (TMG)	Temperature response given steady state and transient profiles. Geometric Math Models models based upon I-DEAS solid models
NIRCam Sensitivity Spreadsheet (NSS)	Sensitivity studies , requirements allocation, and performance assessment
Molecular contamination: Molecular Transfer Kinetics (MTK) ,MOLFLUX	Requirements allocation, Performance assessment. Direct and reflected fluxes (line-of-sight contamination); TSS (Thermal Synthesizer System)
Particulate : Launch Particle Redistribution Model (MPP) , etc.	Requirements allocation, Performance assessment. Particle transport and redistribution in an accelerating, vibroacoustic force environment

3.5.1 Lasagna cooking tools

Our Lasagna project doesn't need the aid of any math models, however, we will be using some pots and pans.

Figure 6 below shows a 12-inch skillet on the left, an eight-quart pot, and a 9x13 inch Pyrex pan. These might be more appropriately compared to our ground support equipment, however, identification of tools and development equipment is best done early.

Figure 6: Tools and Ground Support Equipment

3.6 System Requirement Review

This first requirements and concept definition phase will culminate in a review, however, it is important to actually be heading in the right direction from the very beginning. NASA GSFC Code 301 (ref. 2) has established a good set of topics for NIRCam and other science instruments to follow (Table 2). Systems engineering and product team tasks should be well aligned to develop products that support these areas. A common mistake is to consider these separate from the primary business of developing the instrument. The System Requirements Review will use charts to communicate the progress and status already captured the data products. An aid to injecting this into the program is to develop a clear description of the data products as well as a template for the presentation material. This template serves not simply to describe the format, but includes a list of subtopics and messages that outline the content and represent the whole story. My strong preference is to also develop and conduct product subsystem or component reviews that are in advance and roll up to the System Requirements Review. This may be conducted in a 3 to 4 month period culminating in the System Review.

Table 2: NASA NIRCam System Requirement Review Topics

Mission/Object Design Objective	System Design
Science Requirements	Mechanical
Performance Requirements	Electrical
Technical Constraints	Thermal
Organizational Interfaces	Software
Technical Interface	Ground Support Equipment (GSE)
System Drivers	Operations
Safety Considerations	Planned Test Program
Risk Area	System Performance Verification Matrix
Proposed Design Approach	

This is also an opportunity to benefit from the advice and council of experts outside the immediate program. Each of the subsystem reviews should have a review team. I am an advocate of having representation from all of the program stakeholders as well as independent expert reviewers. The composition of review teams for NIRCam has included topical experts from University of Arizona, from the NIRCam Science Working group, from NASA, independent experts from LM Space Systems Company, independent experts from LMATC, and program Mission Assurance. Additional select reviewers represent a separate organization called Insight and Oversight that reports through an independent organization flow to the company's site Technical Operations lead. This provides a healthy set of beneficial feedback, early enough to incorporate, and from a diverse set of experts.

3.6.1 Lasagna Review Team: Expert Advise

Interim reviews of our simple Lasagna development would be a bit over the top. However, soliciting advise at selective tastings along the way can be beneficial. Moms can be particularly good at this, even without asking. Tasting at the end may be too late to make changes, so get in early and taste frequently. This allows time to make corrections and adjustments. Be open to good suggestions, it makes it a more enjoyable activity.

4. PRELIMINARY DESIGN

4.1 Requirement updates and subsystem requirements development

At this juncture, we have completed the SRR and established the system requirements and design concept. We should now make sure we complete any pending system updates and begin the flow down and establishment of subsystem requirements. It is important to establish a clear set of subsystem requirements prior to significant subsystem design. There will be some parallel requirements and design work. However, prior to roughly the first half of the preliminary design phase, the subsystem requirements should be completed and a stable baseline established. The product teams need design time without the distraction of changing requirements. In addition, the product teams need to understand and own the subsystem requirements. System Engineering should review, approve, and jointly develop these requirements but they should be owned by the product teams. Make sure the traces and rationale are complete and well-understood. Note that the requirement hierarchy has changed and improved. There has been consolidation of parent document ownership and more explicit breakout of subsystem specifications.

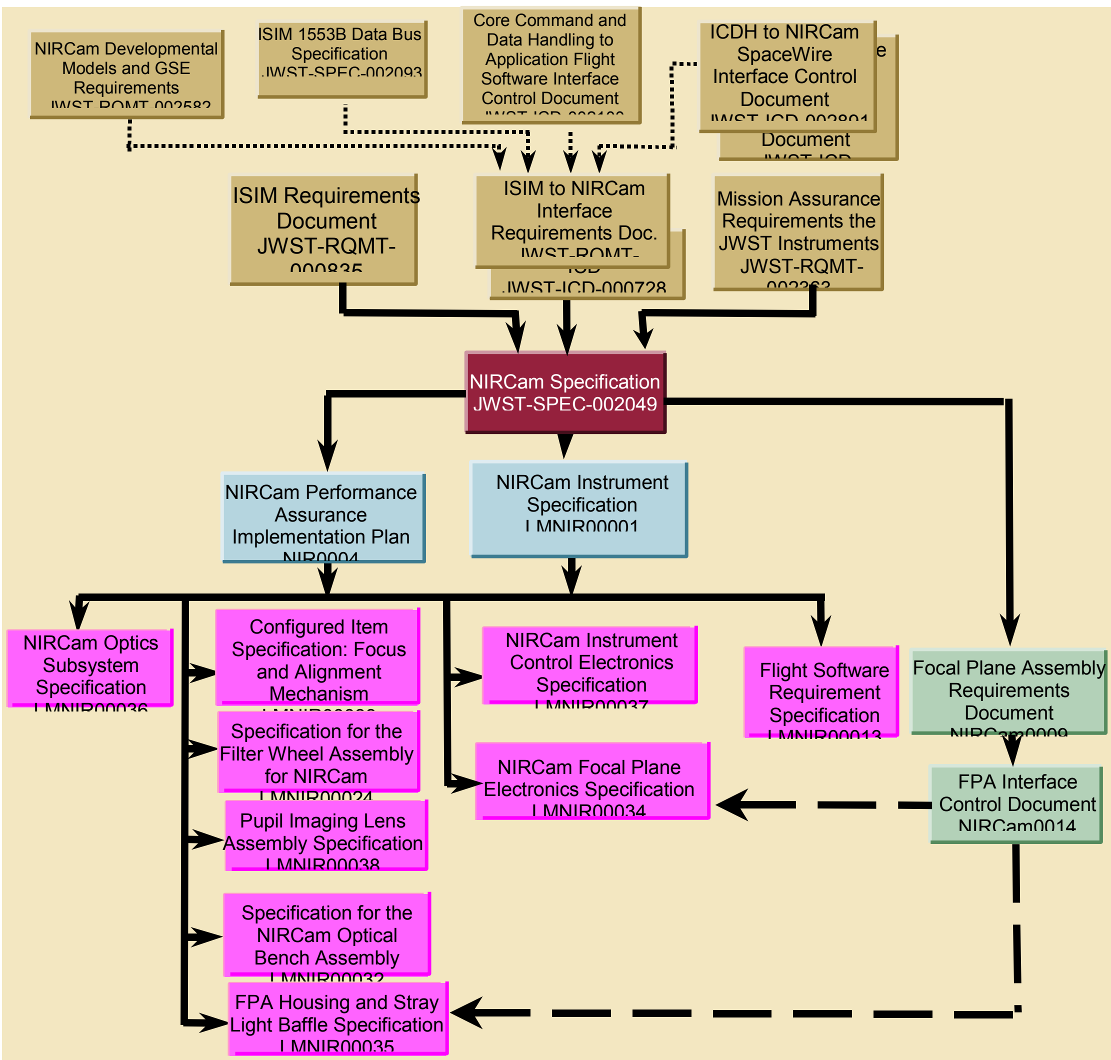


Figure 7: Requirements Hierarchy Preliminary Design Update

During this phase, NIRCam had also transitioned from Microsoft Office products handling requirements to a more capable requirements management tool. This commercial product, called Dynamic Object Oriented Requirements System (DOORS), is structured to allow requirements in separate documents associated with various product architecture levels. The DOORS tool also enables links to parent and child requirements amongst the various modules within the DOORS database. This also allowed the tracking of unresolved requirement issues with attributes indicating an item was still 'To Be Determined' (TBD) or 'To Be Resolved' (TBR). This enables orderly development of complex specifications with varying levels of maturity or completeness amongst the wide variety of requirement types. This was used effectively for the NIRCam specification with links to subsystem specs. In addition, a preliminary verification module can be developed and linked to the actual requirement line items, linking the verification methodology and integration configuration level.

4.1.1 Lasagna components

We have specified the dining objectives, top level requirements, and even listed the ingredients, however, we still need better definition of the lower level layers. This particular recipe consists of three major layers with a repeating sub-layer pattern of noodles, meat sauce, mozzarella, and ricotta cheese. It is difficult to imagine how we could prepare this dish without a good description or definition of these lower level elements.

Figure 8: Lasagna Major Components: Noodles, Meat Sauce, Mozzarella, and Ricotta Cheese

4.2 Interfaces

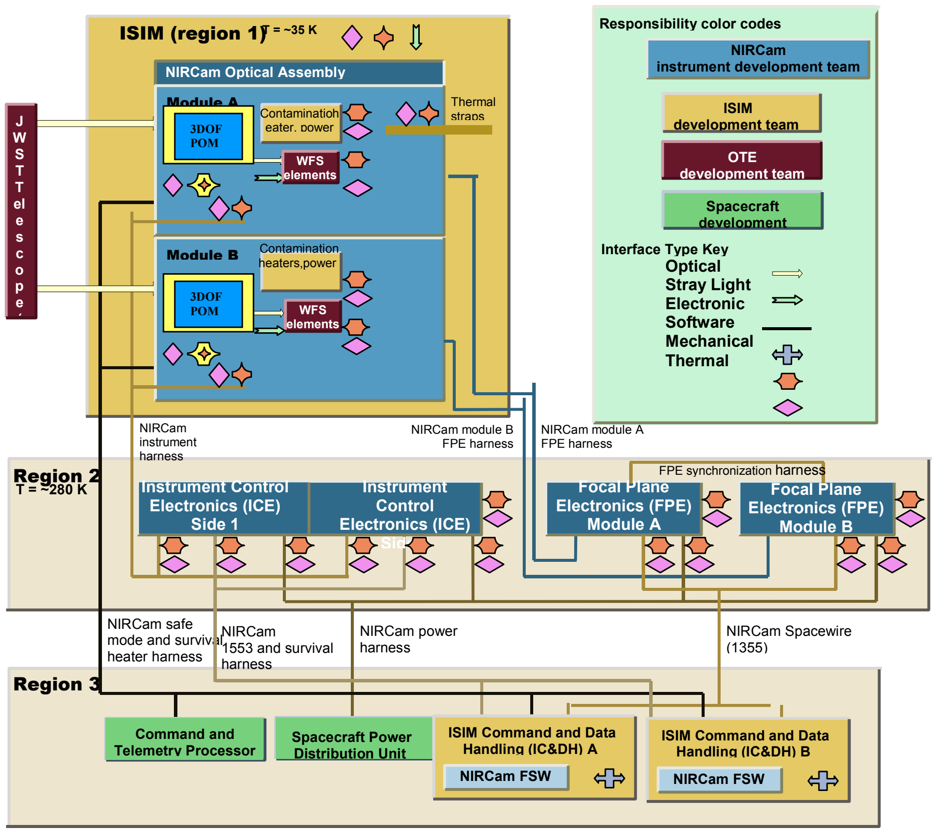
Hard requirements can originate from more than top-level performance objectives. Interface definition starts in the system requirements phase and carefully updated during preliminary design. Stability of requirements and interfaces is an important goal. NIRCam was able to report minimal changes from the system requirements phase with the exception of the mechanical interface (Fig. 10). Structural stability considerations needed by the camera drove different attachment points and envelope. External interfaces are more difficult to define with good agreement because of different development organizations. Two sides of the same interface working to different schedules complicate this. It is best to keep the interfaces simple and defined early. The JWST project made a simplifying and risk reducing decision in the System Requirements phase to shift a Canadian-built tunable filter function out of NIRCam and into the Fine Guidance Sensor. This simplified the Canadian Space Agency team interfaces. This also left the NIRCam imaging functions to the University of Arizona, LMATC, and Rockwell team. This allowed simpler interfaces.

4.2.1 Lasagna Interface Constraints

Surprising at it may seem, we do have a constraining interface in our 9x13 Pyrex pan (Fig. 9) This size pan is more common and fairly inexpensive. Lasagna noodles are available in various dimensions at most grocery stores. I have found the 'extra wide' noodles, when boiled are approximately 3 x 13 inches and fit nicely 3 across. Of course the noodles can by cut, however, it is easier if they fit nicely right out of the box. This is another aid that will make building the lasagna much easier.

Figure 9: Noodle Interface Constraint

Figure 10: NIRCam Interfaces



4.3 Margin management

Good system engineering practice maintains a watchful eye on critical requirements and evolving performance predictions. This began in the system requirements phase and is sustained during this preliminary design phase. Coordinate with the Principal Investigator, customer, and your own product development team. Make sure there is agreement on the requirement and interpretation. Develop a performance prediction that reflects the capabilities of the current design or hardware and software in test. It is the current state of the preliminary design baseline that provides this basis. Decide on the frequency of reporting. This is often done on a monthly basis. There are also considerations for determining what represents a tangible or discernable maturity event that might warrant an update. Frequent reporting is helpful. This provides insight into the quality and robustness of the system design. This insight improves as the program matures. Mitigation plans to correct shortfalls or negative margin can involve improving the performance or reallocation of a parent requirement. NIRCam tracked and continues to track the following key performance parameters (Table 3), in addition, to mass, electrical power, and thermal heat load.

4.4 Preliminary Design Review (PDR)

The preliminary design effort culminates in a formal review. The PDR presents the system design and demonstrates that the design meets all system requirements with acceptable risk. There is an independent review team that is led by NASA GSFC. The review team can and probably will identify actions to resolve technical issues. As with the prior phase, it is important to align preliminary design tasks with this objective. The review is not so much an end item as it is an important event on the road to developing NIRCam. Also similar to the system requirements phase, I have a strong preference to plan and conduct subsystem preliminary design reviews leading up to the system PDR. This builds on a good flow-down of subsystem requirements early in the preliminary design phase. This also helps the product design teams understand how their subsystem should perform. Interfaces and verification methods are defined. Evidence showing sufficient design maturity is needed to assess readiness to proceed with final design. This review is a gate for authorization to proceed to detailed design and fabrication of engineering test unit hardware.

Table 3: Example of NIRCam Key Performance Parameters

Parameter	Requirement	Prediction	Margin = Requirement - Prediction
Sensitivity	10.4 nJy at 2.0 microns 12.1 nJy at 1.1 microns	8.1 nJy at 2.0 microns* 9.8 nJy at 1.1 microns*	2.3 nJy at 2.0 microns 2.3 nJy at 1.1 microns
FPA Operating Temperature/Stability	32K to 40K 0.1K over 4ksecs	32K to 40K (boundary) 0.02K over 4ksecs	nominal 0.08K over 4ksecs
Field of View	>17arcmin^2	18.9 arcmin^2	1.91 arcmin^2
Accommodate Focal Surface Shift	$\pm$5.1mm	$\pm$10.2mm	$\pm$5.1mm
Wavefront error at 2 microns. Worst case point in the field	69 nm	66.7 nm	2.3 nm

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It is also critical to have developed a good foundation of preliminary design data products that provide the details and description of the preliminary design baseline. The briefing charts are a good way to explain this baseline, however, it is the system and subsystem specifications, the preliminary drawings, the preliminary design models, the performance analysis, interface control documents, verification plans, and other engineering memoranda that form the complete preliminary design technical baseline. The NASA GSFC Code 301 group and JWST project office provided a good set of topics to be covered (Table 4).

Table 4: JWST NIRCam PDR Topics

Science/Technical Objectives, Requirements, General Specification	Design verification, test flow and calibration/test plans
Closure of Actions from Previous Review/Changes since the last review	Mission and ground system operations
Performance Requirements	Parts selection, qualification, and Failure Mode and Effects Analysis (FMEA) plans
Error budget determination	EEE Parts Checklist
Weight, Power, Data rate, Commands, EMI/EMC	Contamination requirements and control plan
Interface Requirements	Quality Control, Reliability and redundancy
Mechanical/structural design, analyses, and life tests	Materials and Processes
Software requirements and design	System Performance Verification Matrix
Ground Support Equipment design	Safety hazards identified
System Performance budgets	Acronyms and abbreviations

4.4.1 Early lasagna taste test

Our lasagna recipe calls for browning the meat and simmering the sauce for 20 minutes prior to assembly and baking. This is a good time to have a taste test. Bringing in some independent expert advise is good. Be open to constructive criticism and follow up on good suggestions. Adding a few spices can be implemented at this early phase and might improve the dish. A nice Sangiovese wine will go well with lasagna, as well as, in the kitchen while cooking and tasting.

Figure 11: Expert Advise Early in Development is Good

5. CONCLUSION

Even though I would like to say there is a simple recipe for Systems Engineering that can be applied to your programs, I am afraid I can't. At least if there is, it won't be simple, nor static, nor fit all programs, and it certainly won't guarantee success. However, careful attention to the above process and products will go a long way to improving the probability of success. NIRCam's successful PDR, as evidenced by the outstanding feedback from the NASA review teams, was a combination of good system engineering practice and the quality of the NIRCam design team and their products. We're now ready to enter the critical design phase and prepare a nice Lasagna dinner.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1) 'NIRCam Sensitivity Spreadsheet' developed by Marcia Rieke for NIRCam. Determines signal -to-noise achievable in a given period with the same equation as in Appendix A of the JWST Observatory specification.
2) NASA GSFC Code 301 review guidelines can be found at the following websites:
http://arioch.gsfc.nasa.gov/301/html/301.html
http://arioch.gsfc.nasa.gov/301/html/design.html
http://arioch.gsfc.nasa.gov/301/html/reviews.html