A Curated View of Systems Engineering for Science Missions as Science and Practical Art

INCOSE

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Jonathan Arenberg, PhD

Chief Engineer

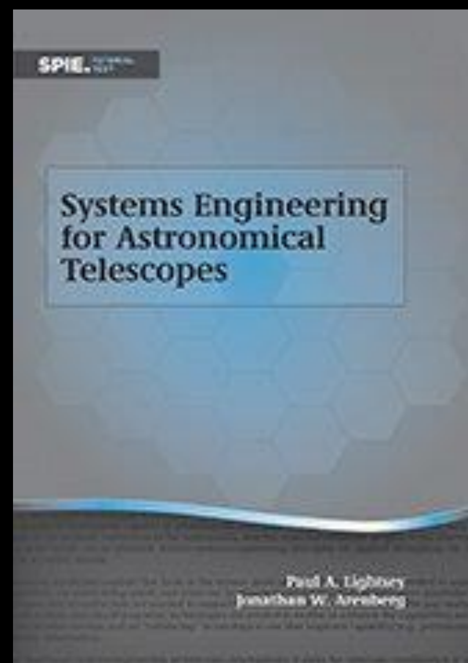
Space Science Missions

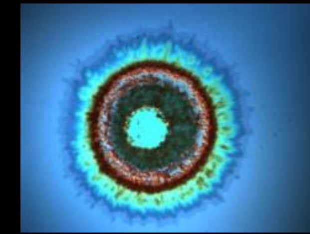
Northrop Grumman Aerospace Systems

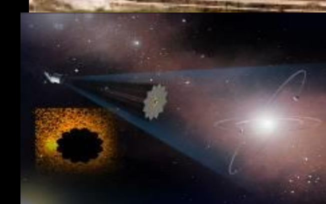
@JonArenberg

Overview and Purpose

- Accept an invitation
- Examine systems engineering as applied to science missions
  - **Discipline**
  - **Art**
- A few lessons learned
- Infotainment
- Questions







What is Systems Engineering?

- Use the dictionary and combine system and engineering….
- Systems Engineering is focused on considering the whole job or problem
  - Global or universal optimization
  - Finding the "best" answer
  - Make the "best" plans
  - Start with your eyes on the finish
  - Telling the complete story
    - At the appropriate level
    - For the right audience

Before a system is optimized (designed), the objectives must be known

What Does "Best" Mean

Best Performance?

or just meeting requirements?

Lowest cost?

Fastest delivery?

Lowest risk (performance, cost, schedule)?

Best Value?

Longest lived?

Balancing "all of the above"?

Big Picture View of SE For Science

- Systems Engineering should be thought of as guidelines
  - **Not a hard one size fits all recipe**
- This is especially true for large space astronomical systems
  - **For new systems there is no book**

Systems Engineering is both Science and Art

Central Problem of System Design For Science

- To design and execute a system capable of producing worthy (new) science, with constraints
  - **Under-defined or improperly defined problem**
  - **New designs or technology**
  - **Complexity**
  - **Imperfect parts**
  - **Finite funds**
  - **Finite time**
    - Celestial schedule
    - Graduation (or Retirement)
- Is SE job for astronomical (scientific) instruments special?
  - **Generally scientific instruments are aimed at doing something new or better than previously achieved**
    - "there is no book for this"
  - **Lots of "new" (non-recurring) engineering means this may be harder than incremental improvements in other areas of engineering**

Process, Orthodoxy, Imagination and Rigor

- Much is said of process
- Process is important but it is never a substitute for doing the right work at the right time
- Many SE processes are aimed to apply to all situations and by necessity very general
  - **Typically don't always apply well to developmental activities**
- These processes are good guidelines, but should not be taken as inviolate, guidelines or statute
- One need be aware of these processes, but be ready to deviate along your own lines if needed
  - **Be able to defend you position with a well presented argument**

To get the right answer you must ask the correct question

- Many problems confronting the systems engineer, especially on very complex systems are posed with the best knowledge at the time they are asked
  - **Knowledge advances**
    - Fundamental science questions
    - How the system operates
    - Assume learning
- As you work through problems you should always reconsider, "are we solving the right problem in light of what we NOW know?"
  - **Applies at all phases of a program or project**
- It is more than ok, it is required, that question being addressed be reconsidered if new information demands it

What makes a good System Engineer?

- Has intellectual curiosity
  - **Multidisciplinary**
    - Has wide range of technical skills
  - **Enjoys interdisciplinary problems**
- Has a “Big Picture” view
  - **Is conversant with fundamental questions; “science smart”**
  - **Comprehensive understanding of the system and how it operates**
- Sees connections
  - **N^2 view**
  - **Knows** $\frac{\partial z}{\partial w_i}$ **for all *i***
- Uses the power of approximations anchored to underlying physics
- Is comfortable with change & uncertainty
  - **Knowledge of probability & statistics is essential**
  - **Understands how to handle “uncertain” uncertainties**
  - **Can juggle chaos and options**

What makes a good System Engineer?

- A visionary skeptic
  - **Active imagination with proper paranoia**
  - **Multi-dimensional risk analyst**
  - **Fault Tolerance management is a key experience/skill set**
  - **Failure Modes and Effects analysis experience**
- Pays attention to resources, margins, and reserves
  - **Capabilities beyond requirements**
  - **Partials for science return and for cost**
- Appreciates the art of systems engineering
- Appreciation of process
  - **Understanding the tool kit (*But tools do not make the artist*)**
- Self-confidence & energy
  - **Hard working & not easily discouraged**
- Self motivated
  - **It is the SE's job to turn over the rocks!!**
- **Likes people**
- **Good communications skills**

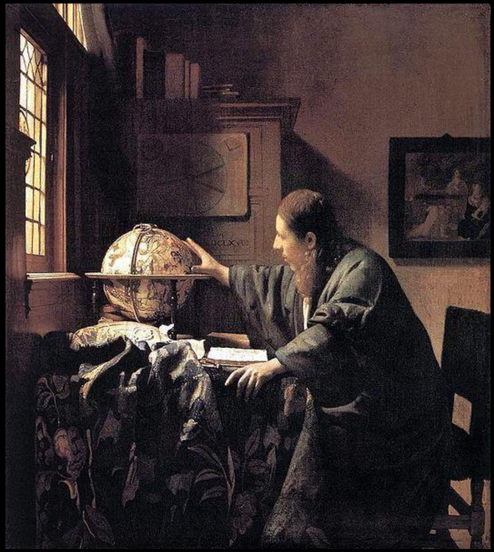
- *Gentry Lee, JPL & Kossiakov, et. al.*

Keys to System Design

- Know how the system works
  - **Be able to explain the concept**
  - **Know the Big Fundamental Problem of the design**
    - Make it central or paramount
  - **Learn how the system fails**
    - Design should mitigate failure
- Have a performance model and keep it current
  - **Know the assumptions and approximations**
    - Relax them or test to validate
- Have budgets for all the key performance metrics
- Understand allocations

Tools of the Trade

- **Budgets and allocation**
- N^2 diagrams
- Requirements traceability
- ad infinitum…..



Derivation of the Law of Error Propagation

- Consider a process with the outcome, z

$$z = f(w_1, w_2 \ldots, w_N) \qquad [1]$$

- The ideal outcome is $z=\mu_z$

$$\mu_z = f(\mu_1, \mu_2 \ldots, \mu_N)$$

- For small deviations, from the ideal set of parameters, μ_i, z is given by the Taylor Series expansion

$$z = \mu_z + \sum_{i=1}^{N} \frac{\partial f}{\partial w_i}(w_i - \mu_i) + O\left((w_i - \mu_i)^2\right)$$

- Ignoring terms of greater than linear order in $(w_i-\mu_i)$ gives the expression for the expected outcome in the case of a non-ideal process

$$z = \mu_z + \sum_{i=1}^{N} \frac{\partial f}{\partial w_i}(w_i - \mu_i) \qquad [2]$$

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f is the system model

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Here are the partials we spoke of earlier

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[2]

Derivation of the Law of Error Propagation

- Subtracting μ_z from both sides gives

$$z - \mu_z = \sum_{i=1}^{N} \frac{\partial f}{\partial w_i}(w_i - \mu_i)$$

- Squaring gives

$$(z - \mu_z)^2 = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial w_i}\right)^2 (w_i - \mu_i)^2 + 2\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left(\frac{\partial f}{\partial w_i}\right)\left(\frac{\partial f}{\partial w_j}\right)(w_i - \mu_i)(w_j - \mu_j)$$

- Taking the expectation value, $E(x)=\int xp(x)dx$, of both sides

$$E\left[(z - \mu_z)^2\right] = E\left[\sum_{i=1}^{N} \left(\frac{\partial f}{\partial w_i}\right)^2 (w_i - \mu_i)^2 + 2\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left(\frac{\partial f}{\partial w_i}\right)\left(\frac{\partial f}{\partial w_j}\right)(w_i - \mu_i)(w_j - \mu_j)\right]$$

Derivation of the Law of Error Propagation

- Since the expectation value of a sum is the sum of the expectations and where left hand side has been re-written since $E[(z-\mu_z)^2]=\sigma_z^2$

$$\sigma_z^2 = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial w_i}\right)^2 E\left[\left(w_i - \mu_i\right)^2\right] + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(\frac{\partial f}{\partial w_i}\right)\left(\frac{\partial f}{\partial w_j}\right) E\left[\left(w_i - \mu_i\right)\left(w_j - \mu_j\right)\right]$$

- Rewriting the right hand side gives

$$\sigma_z^2 = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial w_i}\right)^2 \sigma_i^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(\frac{\partial f}{\partial w_i}\right)\left(\frac{\partial f}{\partial w_j}\right)\sigma_{ij} \qquad [3]$$

- Where the covariance of i and j, σ_{ij} is given by

$$\sigma_{ij} = \sigma_i \sigma_j \rho_{ij}$$

- ρ_{ij} is the correlation coefficient between w_i and w_j
  - **ρ_{ij} can vary between –1 and 1**

Derivation of the Law of Error Propagation

- Using the definition of covariance gives

$$\sigma_z^2 = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial w_i} \right)^2 \sigma_i^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left(\frac{\partial f}{\partial w_i} \right) \left(\frac{\partial f}{\partial w_j} \right) \rho_{ij} \sigma_i \sigma_j$$

- When all the parameters are independent, $\rho_{ij}=0$ which gives the traditional result

$$\sigma_z^2 = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial w_i} \right)^2 \sigma_i^2 \qquad [4]$$

We have [4], what could possibly go wrong?

- As more is learned, which we KNOW will happen…
  - **f might be modified**
    - Design changes
    - Improved understanding
      - Missing physics
  - **N might increase**
  - **Sensitivities change**

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Stuff happens…

Add Reserve

$$\sigma_z^2 = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial w_i} \right)^2 \sigma_i^2 + R \qquad [5]$$

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Why is Adding Reserve Hard???

$$\sigma_z^2 = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial w_i} \right)^2 \sigma_i^2 + R$$

[5]

- Looks like padding
- Makes the lower level tolerances tighter
- The job of systems engineer is to explain why this reserve is necessary and will lower program risk (cost, schedule and performance)
- The more rigor and thought into this the greater the chances of success
- How do you know how big to make R?

How are σ_i assigned?

$$\sigma_z^2 = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial w_i} \right)^2 \sigma_i^2 + R \qquad [5]$$

- [5] is an underdetermined system
- The σ_i are the system tolerances
  - **This is where success or failure lurk…..**
- A set of σ must be determined or "entropy" will find one for you….

Objective Function, U

- An objective function embodies a cost (benefit) to be minimized (maximized) and depends on all the variables of the problem, namely all the μ_i and σ_i
- We can write the objective function (assuming the cost (benefits) of the ith parameter are independent of all others as ui

$$U = \sum_i u_i \left(w_i, \sigma_i \right)$$

- Then the apportionment problem is a simple matter of minimizing (maximizing) U while still satisfying

$$\sigma_z^2 \geq \sum_{i=1}^{N} \left(\left. \frac{\partial f}{\partial w_i} \right|_{w_i = \mu_i} \right)^2 \sigma_i^2$$

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One more thing….there can be more than one objective function

Think cost and schedule

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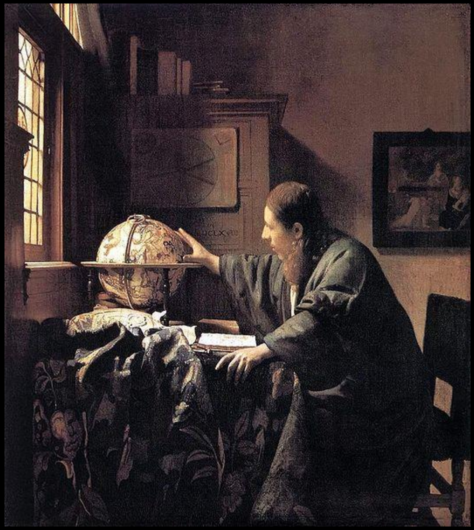
Remember when I said, SE is art???

- Construct U-somehow, any how
  - **Lots of ways to do this**
    - Use the pieces that are known
      - Go get some help
      - Guess and test your guess
    - Understanding U even emotionally is KEY to the design process
      - Keep in mind that is no one has a clue about the u_i at some level, your program is likely very badly priced or estimated in some way!!!

- If you don't think this through and just allocate by other means the resulting design is most likely optimized for something the customer doesn't care about
  - **Who you work for**
  - **Who yells loudest**
  - **Who you like**
- Telling the story of the performance budget is the *sine qua non* of a review
  - **Why does the system look like it does**

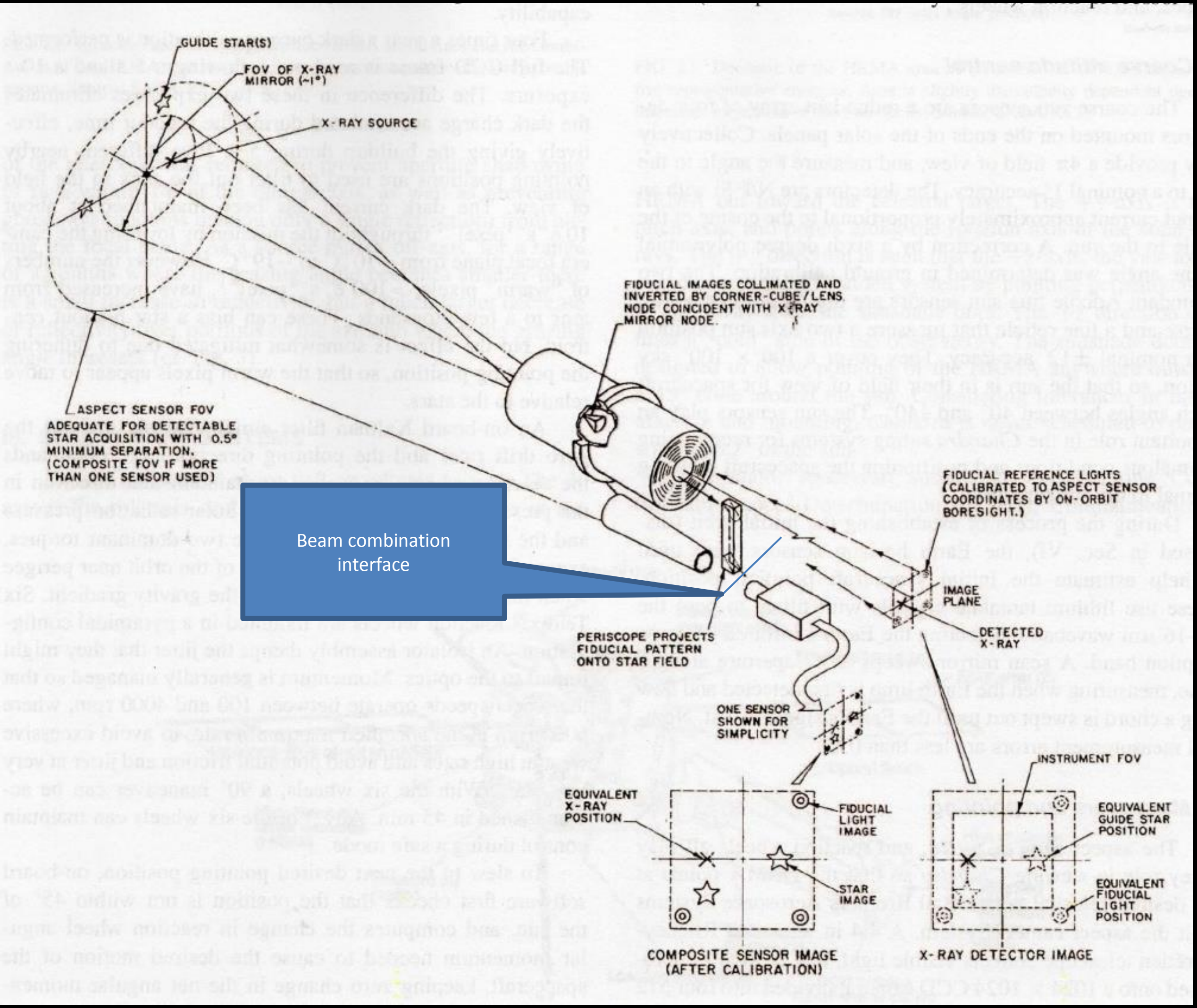


Technical Skills Are Not Enough

- Communication
  - **Written**
    - Reports and documents
    - Specifications
      - Requirements
      - Interfaces
    - Email
  - **Verbal**
    - Presentations
- Organization
  - **Set the right priorities for the SE team**
  - **Library design**
    - How are important decisions recorded and found
- Meetings
  - **Right cadence for the problem**
  - **Know how to run a meeting**
    - Do keep minutes
    - Do record action items
      - Review actions and retire those that are OBE
        - » Have a known policy
  - **Do make sure all are heard**
  - **Make sure you invite everyone**
    - When in doubt over invite
- Teamwork
  - **Big teams will not meet often face to face**
- Cultural Issues
  - **Different organizations do good work differently**

They never told me about this in engineering school: lessons from the front line

Bad Ideas are Hard to Kill



Be Prepared, For Anything

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Communication is Key

Some Problems are NOT Technical.

Some Are Very Technical

Order Statistics formulas

- The distribution of the i^{th} order statistic from n trial is derived as a trinomial where
  - n-i observations at or below ξ
  - One at ξ
  - i-1 observations above ξ
- So the probability density function for the i^{th} order statistic, $\psi(x_{(i)})$

$$\psi_{x_{(i)}} = \frac{n!}{(i-1)!(n-i)!} F^{i-1}\left(x_{(i)}\right)\left[1-F\left(x_{(i)}\right)\right]^{n-i} f\left(x_{(i)}\right) \quad [1]$$

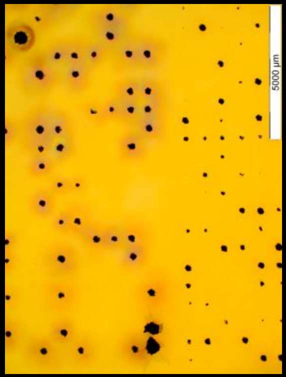
- Mean (expected) value for the i^{th} order statistic, $E(x_{(i)})$

$$E\left(x_{(i)}\right) = \frac{n!}{(i-1)!(n-i)!} \int_{-\infty}^{\infty} \xi F^{i-1}(\xi)\left[1-F(\xi)\right]^{n-i} f(\xi)\, d\xi \quad [2]$$

- Variance of the i^{th} order statistic, $V(x_{(i)})$

$$V\left(x_{(i)}\right) = \frac{n!}{(i-1)!(n-i)!}\left[\int_{-\infty}^{\infty} \xi^2 F^{i-1}(\xi)\left[1-F(\xi)\right]^{n-i} f(\xi)\, d\xi - \left(\int_{-\infty}^{\infty} \xi F^{i-1}(\xi)\left[1-F(\xi)\right]^{n-i} f(\xi)\, d\xi\right)^2\right] \quad [3]$$

TRW



Order Statistics Basics-Continued

- Mean (expected) value for the 1^{st} order statistic, $E(x_{(1)})$

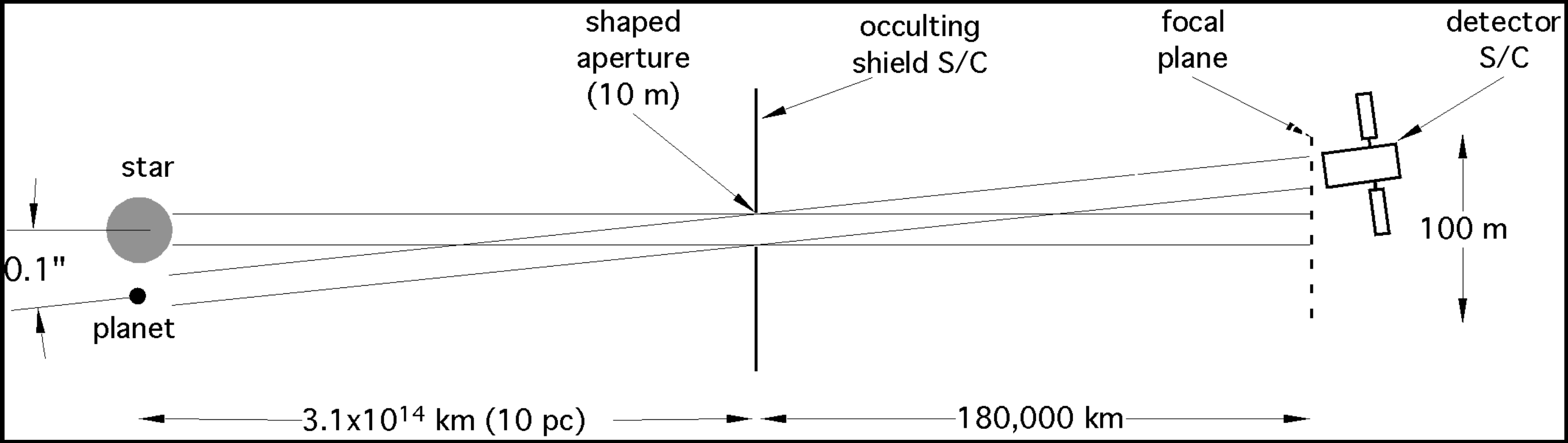
$$E\left(x_{(1)}\right) = \Lambda(n) = n\int_{0}^{\infty} \xi\left[1-F(\xi)\right]^{n-1} f(\xi)\, d\xi \quad [4]$$

- Variance of the 1^{st} order statistic, $V(x_{(1)})$

$$V\left(x_{(1)}\right) = n\left[\int_{0}^{\infty} \xi^2\left[1-F(\xi)\right]^{n-1} f(\xi)\, d\xi - \left(\int_{0}^{\infty} \xi\left[1-F(\xi)\right]^{n-1} f(\xi)\, d\xi\right)^2\right]$$

TRW

Don’t Prejudge Ideas



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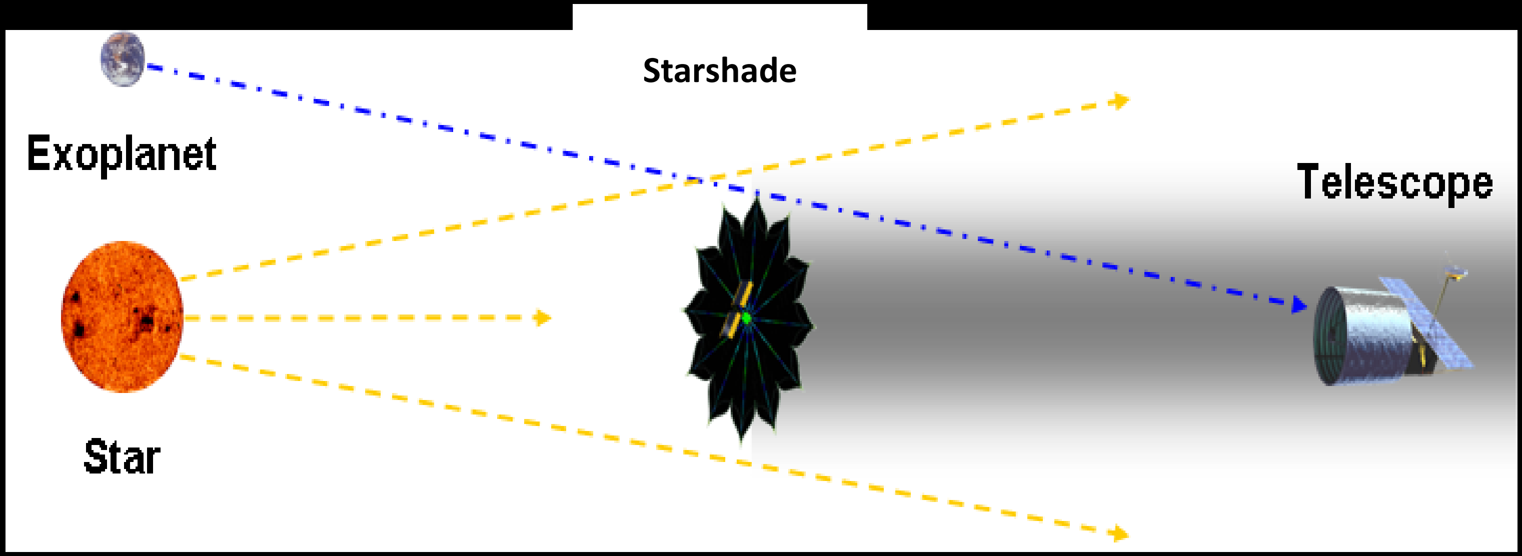
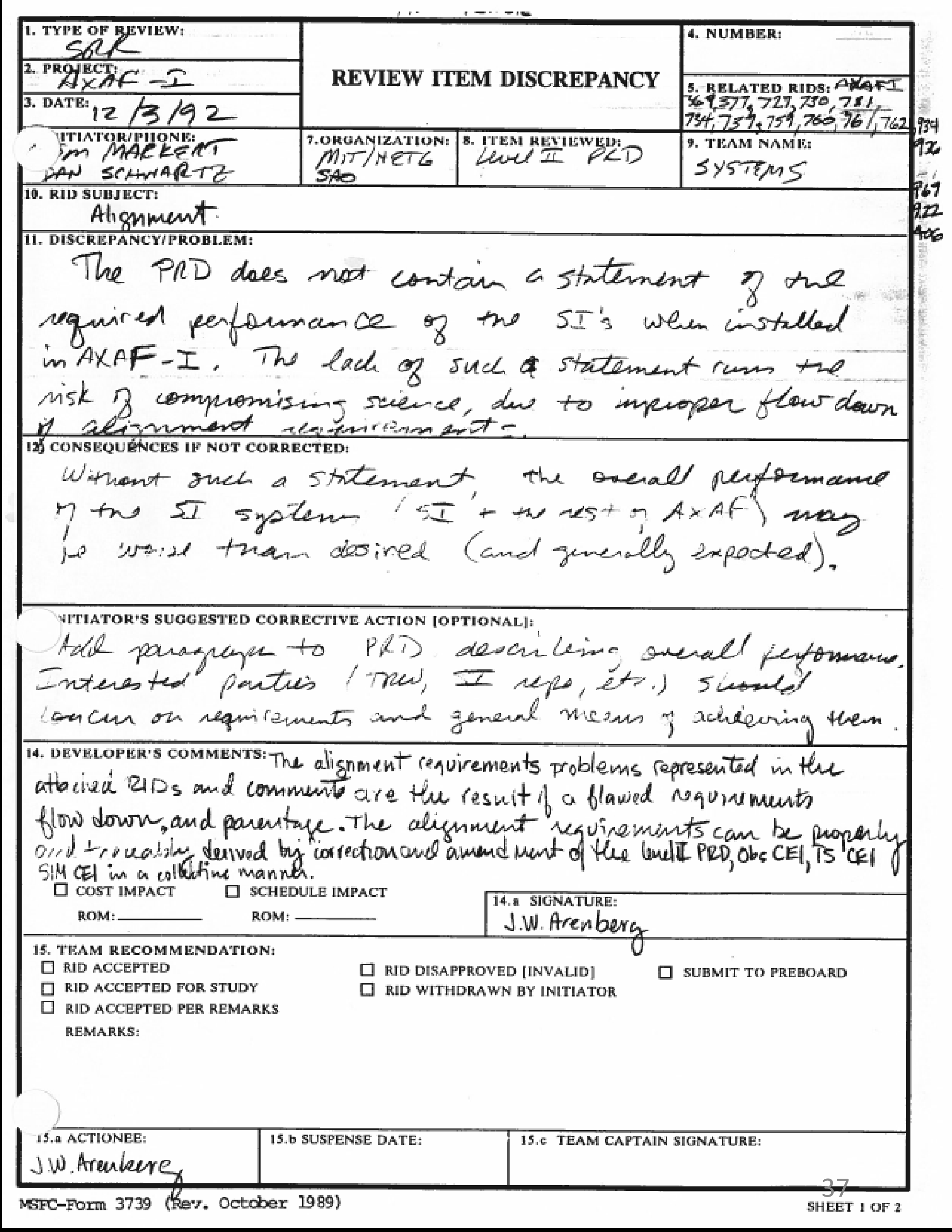


Challenge tight Requirements



1. TYPE OF REVIEW: SAR
2. PROJECT: AXAF-I
3. DATE: 12/3/92

REVIEW ITEM DISCREPANCY

4. NUMBER:
5. RELATED RIDS: AXAF I 369, 377, 727, 730, 731, 734, 737, 759, 760, 761, 762, 934, 926, 967, 922, 406

6. INITIATOR/PHONE: Jim MARKERT / DAN SCHWARTZ
7. ORGANIZATION: MIT/HETG SAO
8. ITEM REVIEWED: Level II PRD
9. TEAM NAME: SYSTEMS

10. RID SUBJECT: Alignment

11. DISCREPANCY/PROBLEM:
The PRD does not contain a statement of the required performance of the SI's when installed in AXAF-I. The lack of such a statement runs the risk of compromising science, due to improper flow down of alignment requirements.

12. CONSEQUENCES IF NOT CORRECTED:
Without such a statement, the overall performance of the SI system (SI + the rest of AXAF) may be worse than desired (and generally expected).

13. INITIATOR'S SUGGESTED CORRECTIVE ACTION [OPTIONAL]:
Add paragraph to PRD describing overall performance. Interested parties (TRW, SI reps, etc.) should concur on requirements and general means of achieving them.

14. DEVELOPER'S COMMENTS: The alignment requirements problems represented in the attached RIDs and comments are the result of a flawed requirements flow down, and parentage. The alignment requirements can be properly and traceably derived by correction and amendment of the Level II PRD, Obs CEI, IS CEI, SIM CEI in a collective manner.

☐ COST IMPACT ROM: ______ ☐ SCHEDULE IMPACT ROM: ______

14.a SIGNATURE: J.W. Arenberg

15. TEAM RECOMMENDATION:
- ☐ RID ACCEPTED
- ☐ RID ACCEPTED FOR STUDY
- ☐ RID ACCEPTED PER REMARKS
- ☐ RID DISAPPROVED [INVALID]
- ☐ RID WITHDRAWN BY INITIATOR
- ☐ SUBMIT TO PREBOARD

REMARKS:

15.a ACTIONEE: J.W. Arenberg
15.b SUSPENSE DATE:
15.c TEAM CAPTAIN SIGNATURE:

MSFC-Form 3739 (Rev. October 1989)

SHEET 1 OF 2

Respond Overwhelmingly

Solve problems by thinking all the way to the end

Lessons Below the Line

- Meet face to face
  - **Problem of the “Mute Button Tough Guy”**
- New ≠ Better
- Never say no to work
- Learn how to name things
  - **Call things by correct names, saga of the AAS**
- If you get a formulated problem it is probably wrong
  - **AXAF Magnetic broom**
- When challenged, respond overwhelmingly
  - **APD error bar**
- Sometimes the dragon wins….

One Final Thought

It is not a sin to make mistake, it is a sin to repeat one

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Make a new mistake

Thanks for listening.