Systems Engineering for Space Based Applications

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Satellite Orbits

- Satellites can operate in several types of Earth orbit. The most common orbits for environmental satellites are geostationary and polar, but some instruments also fly in inclined orbits. Other types of orbits are possible, such as the Molniya (Better view, but periodic: two orbits per day, ~10 hour duration) orbits commonly used for Soviet spacecraft.

- **Geostationary Orbits**
- **Polar Orbits-**Used for low Earth orbits mostly: builds an Earth image in swaths
- **Inclined Orbits**

- http://science-edu.larc.nasa.gov/SCOOL/orbits.html

Observation Is Through The Atmosphere

- The hard Earth is surrounded by an atmosphere (~50kM thick)
  - Must look through it to observe clouds (10kM) and Earth features (on-ground)
- Recognition of atmospheric interaction with our observational sciences is a major step in Earth surveillance understanding

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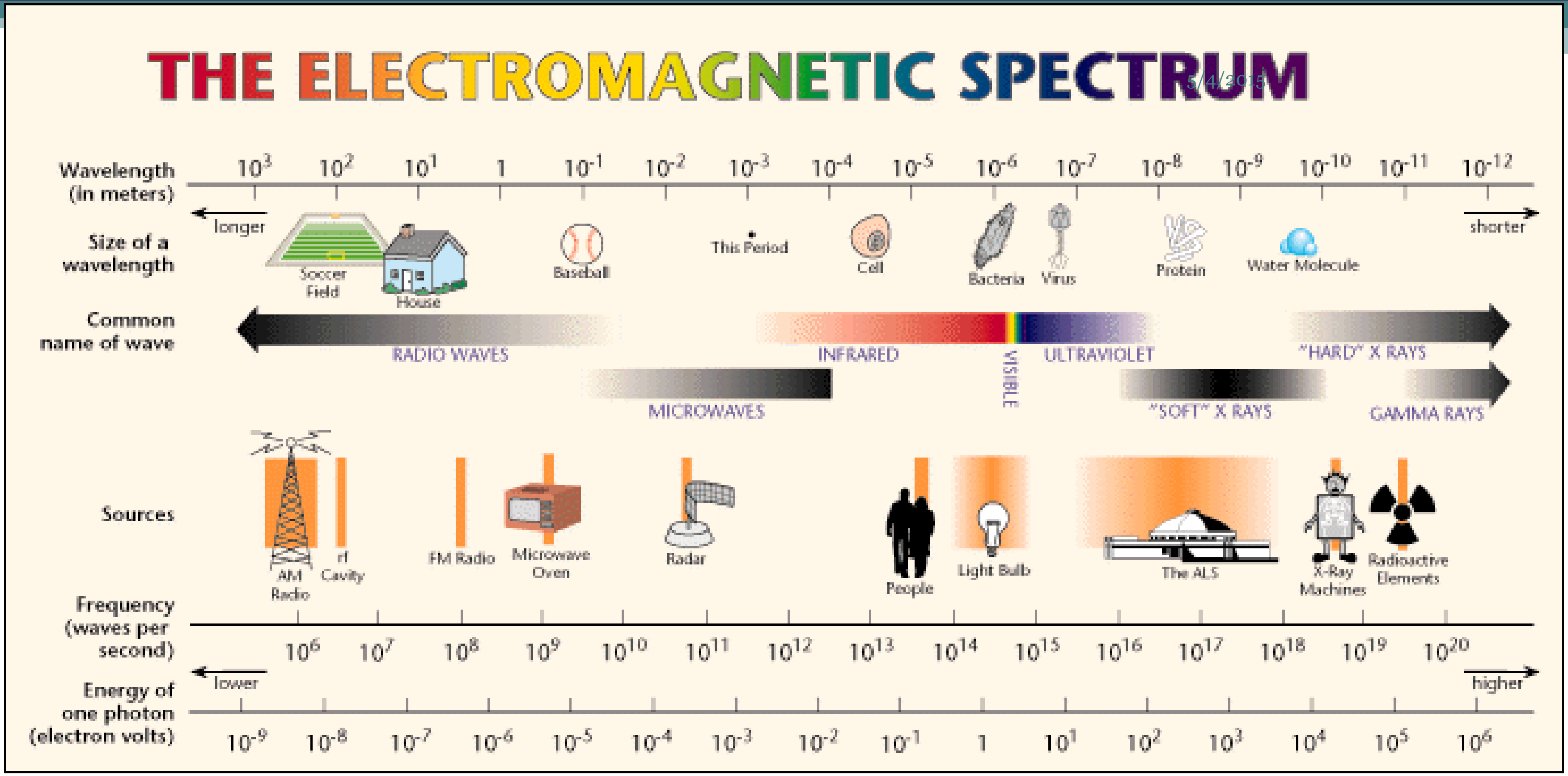
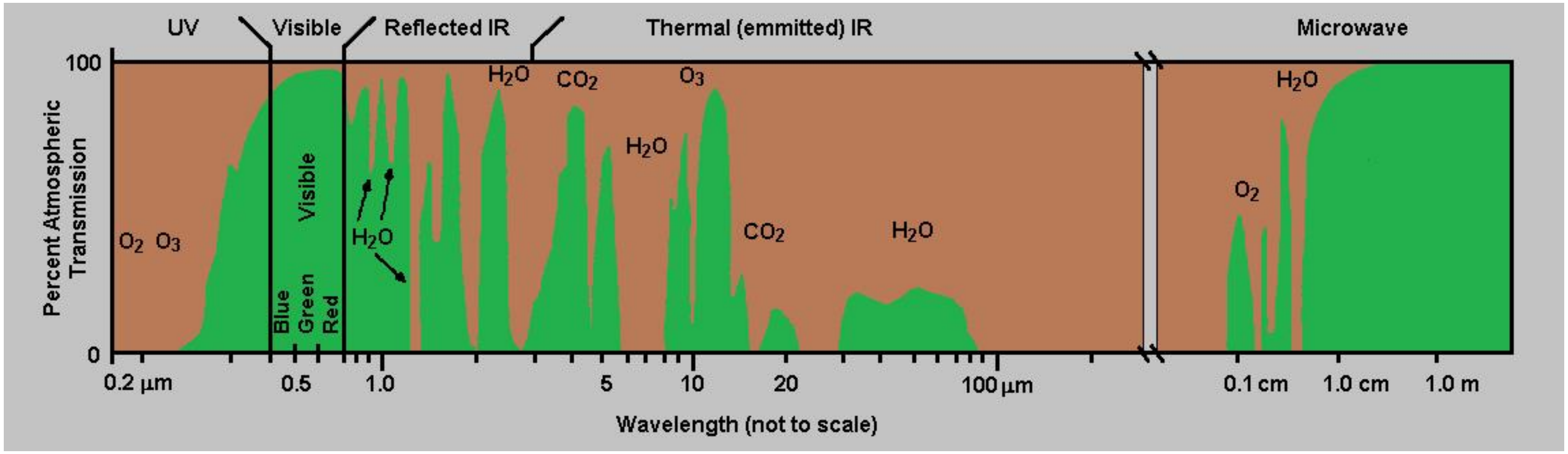

THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
lower
higher
Energy of one photon (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^1 10^2 10^3 10^4 10^5 10^6


UV
Visible
Reflected IR
Thermal (emmitted) IR
Microwave
100
0
Percent Atmospheric Transmission
O_2 O_3
Visible
Blue
Green
Red
H_2O
H_2O
CO_2
O_3
H_2O
CO_2
H_2O
H_2O
O_2
0.2 µm
0.5
1.0
5
10
20
100 µm
0.1 cm
1.0 cm
1.0 m
Wavelength (not to scale)

Designing Satellite Sensor Constellations And Orbits

- Important to convey the system
- More important is making the vision accurate. Develop requirements
  - Number of assets
  - Viewing geometries
  - Coverages
  - Revisit times
  - Thermal environment
  - Access to surveyed areas
  - Ground stations
- Start the thought process "What is your job"
  - Design of a major system is a team action
  - For example the SBIRS constellation has ~1000 requirements that must be satisfied

System Engineering Is An Inexact Science

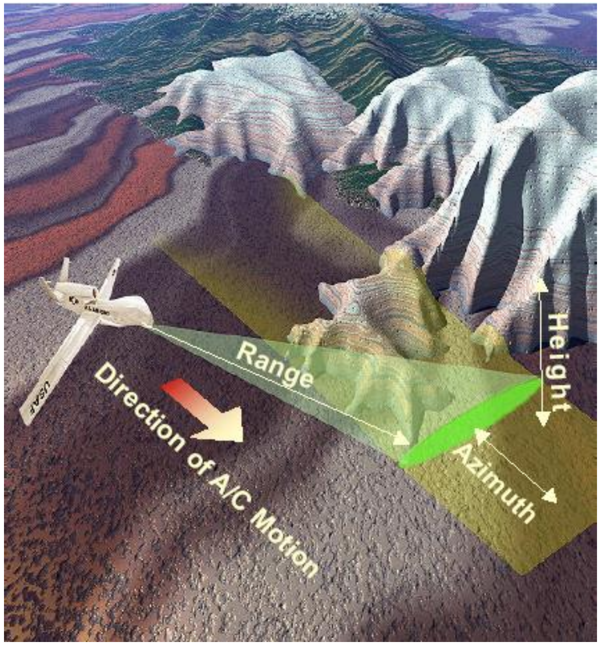
- First – make sure you are within the laws of physics
  - Detection of a signal and its characterization must include
    - Unique attributes of that signal
    - Recognition of the timelines involved
    - Respecting Nature
  - Rejection of false signals
    - A simple two-by-two "confusion" matrix is always helpful

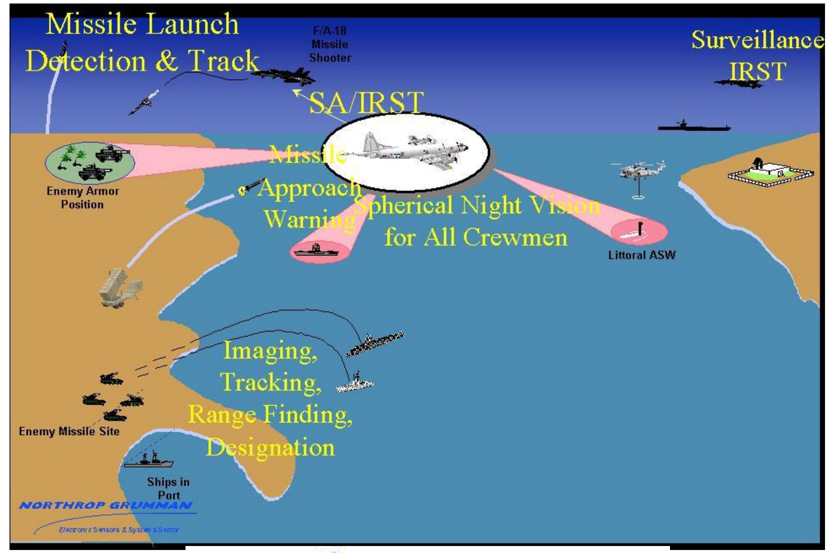
Confusion	Target	No Target
Target	90	5
No Target	10	95

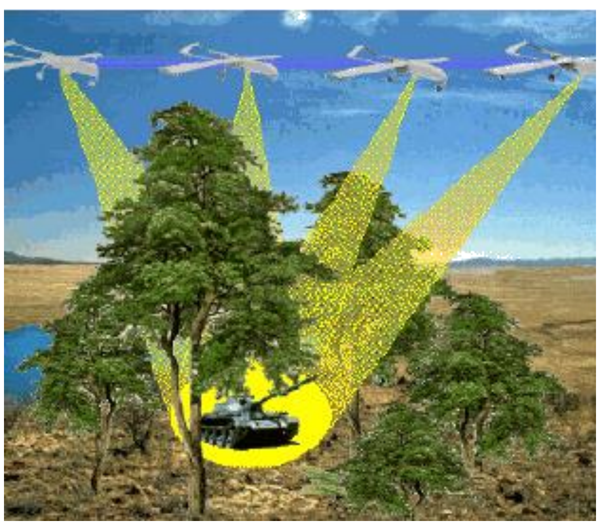
- **Why doesn't it all add to 100%**
- **Are there are other states in the matrix**
- **You are free to specify performance and put some margin in your pocket**
  - **Everyone should carefully husband some performance margin because you'll be eaten up by nature**

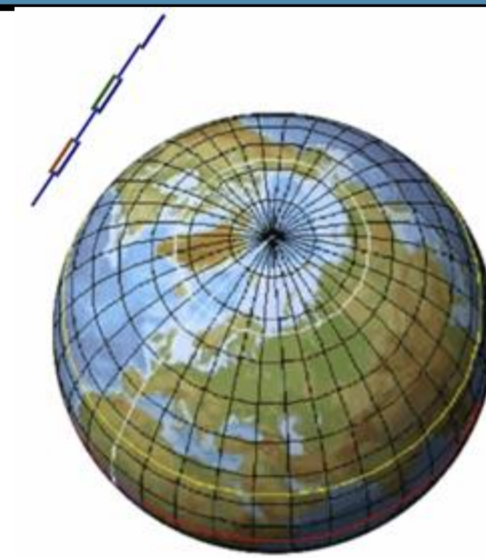
Reserving Margin Is Important To You And To Your Customer
He Doesn't Always Know Exactly What He Wants

Surveillance – Earth Surveys









Mission Needs (Why Build It)

- Understanding of what about the mission and/or its outcome is
  - New
  - Unique
  - Special
  - Why it is needed

- Identification of the users
  - Those that will execute the mission
  - Those that use the data

- Identification of what is critical
  - To the customer
  - And user community

Mission Concept Of Operations: CONOPS

- Who are the players in the mission:
    - Blue assets: on-board systems, off-board systems, other platforms
    - Red assets: Targets and Threats
    - Neutrals
- What is the goal of the mission
    - What are the steps required to achieve that goal.
- Description of battle-space (for a military system)
    - The terrain, time of day, time of year
    - Location of blue and red assets and neutrals
- Mission Timelines
    - The order of the steps
    - What each of the players are doing at each point in time
    - How do each of the players interact

Rebuild a CONcept of OPerationS
Take the customer's viewpoint and elaborate it so that you end up
Doing What You Say You Will Do

Requirements

- Several Levels of Requirements
  - Operational
    - What the customer/user wants/needs, as derived from the mission needs and CONOPs
  - System
    - Derived from the operational requirements
    - Describes what the system must do
    - Derived based on trade studies
  - Sub-system and component:
    - Derived from the system requirements.
    - By trade studies or budget allocations.
- Traceability is essential
  - Identify source of requirement and supporting documentation
  - Link to the next highest level must be clear

Requirements

- All requirements must be properly normalized:
  - Do not specify the same requirement in more than one place
  - Do not specify requirements that can be derived from other requirements
  - Do not leave out key assumptions
  - Do not specify a time to survive without providing a definition of how survival is to be assessed, or a probability of detection without a probability of false alarm
- Operational
  - Keep the number of requirements to a minimum.
  - Should only reflect what the customer wants the system to do,
  - NOT how it should do it
- System and sub-system
  - Derived from flow down process
  - Should reflect subsystems need to do to meet operational requirements
- Build an Interface Control Document
  - Determine the exact interface between subsystems

What do we mean by requirements?

A Transaction Example

Requirements Analysis

I want to write 13 million words every day on a yellow pad of paper in 14 point Century Gothic

I want a yellow pencil with a pink pearl eraser that is 6 to 7 inches long and soft (number 2) and will last for 10 years with normal usage

I am soliciting only the leading contractors for pencils in the USA

Let me propose a program to develop, test and deliver the product to you

For budgeting purposes, what is your ball park cost

$0.38 PER PENCIL, $7,200,000 FOR THE TEST PROGRAM, AND PROGRAMMATICS

My budget will be sorely stretched so you will have to streamline your development and test program

OK– lets get started with a complete requirements analysis which I will do on my Bids and Proposals money. My only requirements back to you are:

1) I need access to you and your technical people to discuss my analyses results of your requirements, and
2) You include me on your bidders list to compete for this procurement.

Assure the program is Real – Assess the areas that the customer is willing to negotiate – Assure you have access to him throughout the process.
NEVER PLAN TO SURPRISE HIM WITH NEW INFORMATION IN A PROPOSAL

A Transaction Example

Analysis

- Does the customer know what he wants?
- Has he understated requirements: can you propose a novel solution
- He may have over-specified requirements (yellow pencil with *pink pearl* eraser)
  - What he really needs is an implement to write 13 Mwords/day for 10 years!
- How does he know that he is buying what he contracted for?
  - A test program is the answer – no more promises and fancy viewgraphs
  - Hard test data is unassailable
    - It is really difficult to sell-off faulty data, don't even try to
- When the buyer—seller risk is established and you all know what you're signed up to AND you have agreed to price and performance, you execute the program – we'll discuss that later – and you deliver the product: then WHAT?
- After sale support and marketing – an EO-IR Earth surveillance system will always provide surprises. Do you think you know everything that it can do? ANSWER NO!
- But this is OK, because now you can build a continuing partnership with the customer – provide him the things he didn't know he needed, but is now sufficiently well educated to appreciate AND he trusts you to provide!

The Easiest New Sale Is To A Satisfied Old Customer

Program Start

You've been successful in obtaining a major development program – Now What?

- Proposed design – kickoff meeting (KO)
  - Post award review, do we have a meeting of the minds at this level?
  - Clarifications and agreement on program execution risk elements

  Evidence of achievable requirements – pre-award hardware or breadboard performance data
- System Requirements Review (SRR)
  - Layout the top-level requirements and one level deeper flow-down guidance
  - Agree upon the design documentation depth – should mimic the proposed level

  Show flow-down structure and detailed program plan to retire risk elements
- Preliminary Design Review (PDR)
  - Complete flow-down structure in place with a full set of subsystem requirements
  - Subcontractors and vendors picked, under contract or in competition
  - PDRs at each major subcontractor should be held concurrently or directly after system PDR

  Development hardware/software – evidence of achieved reduced risk through sub-system maturity
- Critical Design Review (CDR)
  - Firm specifications and performance data of prototypes for critical subsystems
  - Adjustment and re-allocation of margin to cover perceived shortfalls

  Brassboard and engineering software maturity – designs reduced to practice – specification realism

Program Execution

You got through a CDR – Now build the item

- Sub-System Hardware Status Reviews
  - On-going insightful reviews into development, integration, test of subsystems

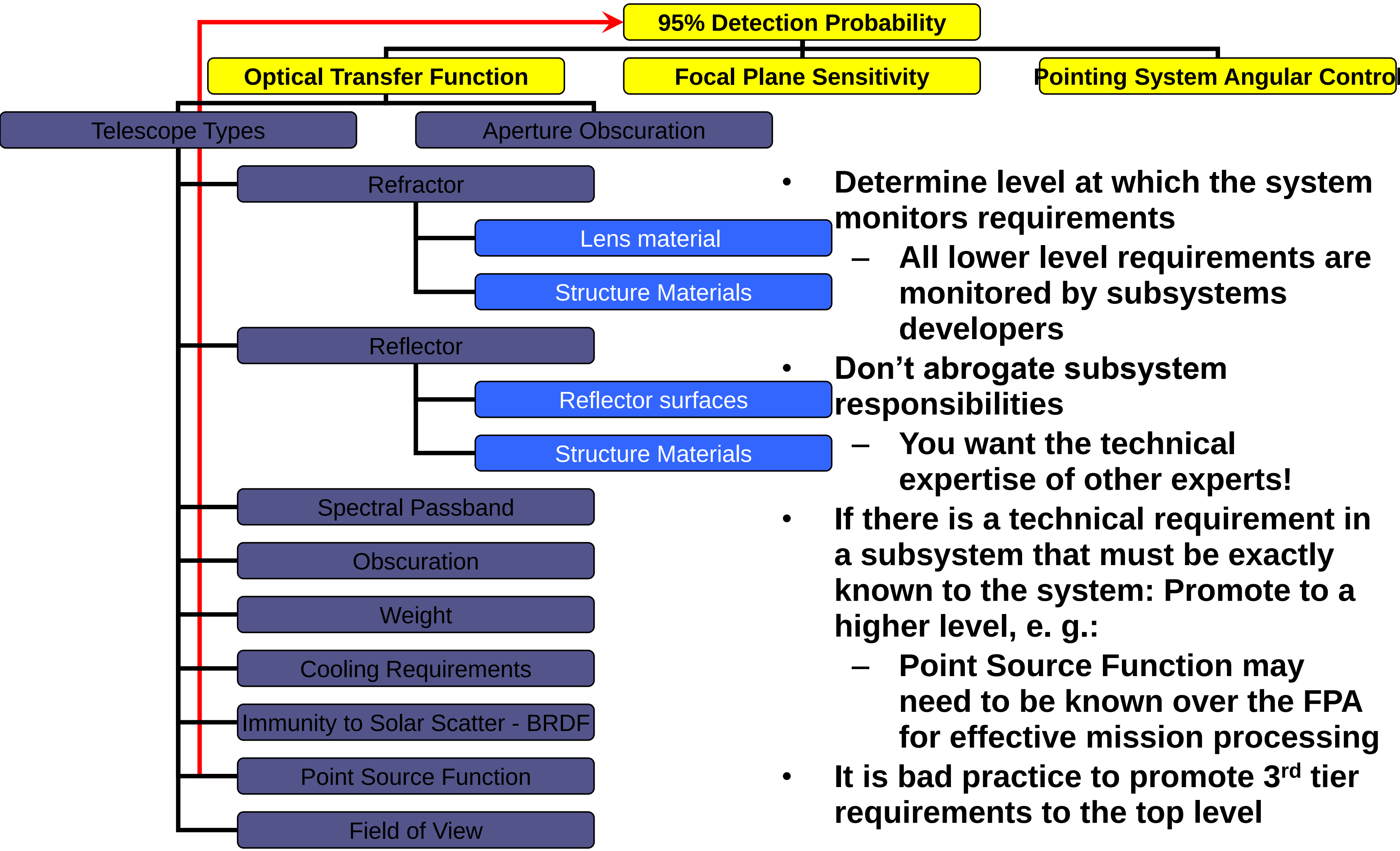
  Payload integration reviews show how interfaces are being met – Interface Control Documentation development and correctness is paramount – everyone build to interfaces – cannot be over emphasized – WRITE IT DOWN
- Test Readiness Review
  - Facilities, controls, and hardware readiness review prior to test execution
  - Pass—Fail criteria established with clearly agreed-to uncertainties

  Tests are the most expensive parts of a space program – not to be minimized
- Consent to Break Review
  - Test complete – does everyone agree?

  Is the test phase over? Have we obtained all the data we must have to sell-off the hardware/software? What are the deficiencies? How will we resolve these? What were the test anomalies and failures? Have all of these been mitigated
- Requirements Verification Review
  - Proof that the item meets its requirements

  Formal submittal to prove that the item meets its requirements. Many RV Reports can be written. Often as many as there are requirements. This process is often done after a major test program, uses test data and normally accurate math models as well.

Program Execution: Flowdown Example



- Determine level at which the system monitors requirements
  - All lower level requirements are monitored by subsystems developers
- Don’t abrogate subsystem responsibilities
  - You want the technical expertise of other experts!
- If there is a technical requirement in a subsystem that must be exactly known to the system: Promote to a higher level, e. g.:
  - Point Source Function may need to be known over the FPA for effective mission processing
- It is bad practice to promote 3rd tier requirements to the top level

Quality And The House – 1

- What does the word "Quality" mean?
  - Excellence, Superiority, Class, Value, Worth
  - "The general standard or grade of something"
- Lets redefine it – in measurable terms
  Quality = Conformance to Requirements
- Now we can measure the quality of an entity by measuring how well it meets or exceeds its requirements
  - We just need a ruler!
- We need an Importance ruler – returning to the pencil
  - If the customer needs yellow finish on the pencil above all else, yellow gets a large score (say, 9 of 10)
  - Pink eraser is not as important, say 3 of 10
  - Number 2 softness, say 6 of 10
- Can we measure our design – Conformance to requirements [0, ½, 1]
- Table at the right is an elementary method to measure

Rqmt	Yell	Pink	#2
Weight	9	3	6
Meets	½	1	½
Quality	4.5	3	3
Q-Score	10.5/30		

How would you Grade this Design?

Quality And The House – 2

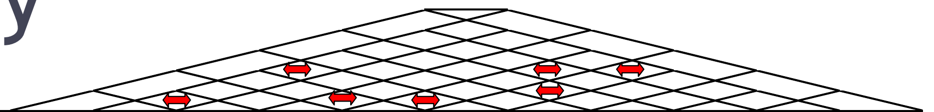
- Measuring the design requires an assessment of the relative importance of requirements
- At right we did best for the least important element
  - Need to push up our score for "Yell" and "#2" categories
  - OR get a reassessment of the requirements
- Interrelationships now rear their ugly heads
- The process is EXTRAORDINARILY critical to proposing and designing a system that the customer wants!
- How do you assess whether providing a pink eraser *may reduce the reliability over life of the pencil*?
- House of Quality Framework was invented – consider using it

Rqmt	Yell	Pink	#2
Weight	9	3	6
Meets	½	1	½
Quality	4.5	3	3
Q-Score	10.5/30		

This simplistic approach leaves us wanting – we need more insight before we decide on a design

The House of Quality

- House of Quality is a device to assist with
  - Trades
  - Interrelationships
  - Pareto's Law (80-20)
- [Example is hyperlinked]
- List the *Needs* of the system in a column
  - Guess or analyze the importance (weights) of each *Need*: Use a 10 scale
- *Attributes* are listed in a row
  - Cross-correlate each *Attribute* to each need
- The "roof" identifies which *Attribute* affects another
  - If you change one, prepare for impact on the other
- Expand the House to lower and lower subsystems
  - *Attributes* become *Needs*



Attributes / Needs	Weighting	Pointing mirror	Telescope Aperture	Cooling System	Focal Plane Configuration	On-Board Processing	Mechanical Structure	Power System	Comm System	Redunancy	Payload Constell
99% On Line	9			9			9	9	9	9	
Hemispherical coverage	9	9			9						
<10 second Revisit Time	6	6				6					
Stereoscopic view	6										6
95% Target Detection	9	9	9		9	9				9	
0.01% False Target Detection	6	6	6		6	6					
Performance independent of Cloud-Fill	3					3					
Target Trajectory ±1°	3	3	3		3	3					
Target Velocity ±100 m/s	6	6	6		6	6					
Comm to Mission Control Station	9								9		9
Line-of-Sight Stability	9						9				
All Raw Data Available	6					6			6		6
Secure Commo	3								3		3
Weighted Sum		39	24	9	33	39	18	9	27	18	24

This Process Takes Months for a Real System – Don't Foreclose on its Power

Models: $F = ma$

- To build a payload for space (or ANY) you need math (heuristic) models
- Role of modeling is essential to good Systems Engineering
- Quickly and because you should now have an appreciation for this, Models
  - Are cheaper than hardware
  - Do not supply all that you need to know
  - Should be re-baselined with new data
  - Should have an open-architecture so that you can easily improve fidelity as the design matures
- Consider this elementary example, in some theoretical system with subsystems characterized by R, T and S:
  - Performance, P, equals $R^2 \times T^{3/2} \times S^{-1/2}$, then from the chain rule we know that
  - $\frac{dP}{P} = 2\frac{dR}{R} + \frac{3}{2}\frac{dT}{T} - \frac{1}{2}\frac{dS}{S}$
- A math model can start to depict the interrelationships between the subsystem performance variables
- Can a deficiency in T be made up by a sufficiency in R or S?
  - At least we have a start!
  - We can ascertain the relative importance of the subsystems

We Have To Propose Work To Gain Work

- The customer – any customer – is going to pay for goods and service that he needs
- He has a charter to buy, procure, build a capability, knowledge base, whatever to <u>his</u> customer – many times that is us: so it is right back at us!
- The customer will set about with sets of requirements that he conceives is necessary to obtain the goods and services he needs
- Our best posture is to provide him with quality services and merchandise that will serve his needs
- Primary to this is to assure we are ON THE SAME PAGE
- Any good customer – that has been burned before – recognizes that formal and/or informal feedback to their stated requirements is essential
  - Tell them what it costs and ALWAYS give them an option
  - Even if you are dead-to-rights sure of what you say, don't show hubris – be humble and, if at all possible, *make it their idea*.
- Your job is to build the highest quality system you can – remember the definition of quality

Proposals Are Serious

- In today's sophisticated world, if you deceive, you'll never win
- Propose what you believe is the best solution to the problem presented to you
  - Try out alternate solutions
  - Bid so that the requirements are satisfied
  - Don't embellish
  - Don't lowball: you'll get caught in cost credibility

If the customer asks for X and you propose Y without convincing him that Y is a righteous solution, YOU LOSE

Proposal Contents

Proposals for work should strive to convince the customer that your approach and your product fulfills his needs

How to convey this essential information

1. Don’t minimize any aspect of the proposal
2. Structure your response to his RFP in accordance with his numbering system
3. Respond to each section as if in isolation between sections. Although you may refer back and forth in your proposal, consider that a different person will be reading only his assigned parts of your overall proposal
4. Have a management approach
5. Show a program plan from inception to final product delivery
6. Detail and layout his requirements and your product’s performance side-by-side: identify positive and negative performance margins
7. Respond to his requirements for risk management and risk mitigation approaches. Risk: means a chance of not getting product to meet requirements
8. For any unresolved or disputed requirements, show how you intend to close out options and solidify the design early-on in your proposed program
9. Develop a cost model and show how you estimated costs
10. Identify your sub-contract teams and their ability to meet your flowed-down requirements
11. Include resumes and qualifications of your key staff members

Proposal Structure

Proposals may have many structures – you want to convey two essential facets

1) Competence
2) Ease of evaluation

To show competence you must show your ability to deal with the technical aspects of the design

You must structure your proposal so that the salient features of your design are immediately evident

You should "ghost" your competitor's approach and show how your design is superior to your competition by direct comparison

To assure ease of evaluation:

1) Follow the RFP outline
2) State your case once and only once
3) Provide a very top-level summary with an index to the more detailed analyses that supports your summary
4) Do not provide surprises – unless you KNOW that the customer is looking for a very high-risk research program, show your approach is well founded and grounded in achievable technology.

Proposal Team

Proposals must show your capability and your confidence in taking on the job

How to convey this essential information

1. Have a team structure that mirrors the customer structure
2. Select a proposal manager
3. Select a chief engineer for the technical parts
4. Select sub-contract manager or managers
5. Show how your team is the most efficient for the product
6. Show how your team will assure the customer that he is to receive a quality product

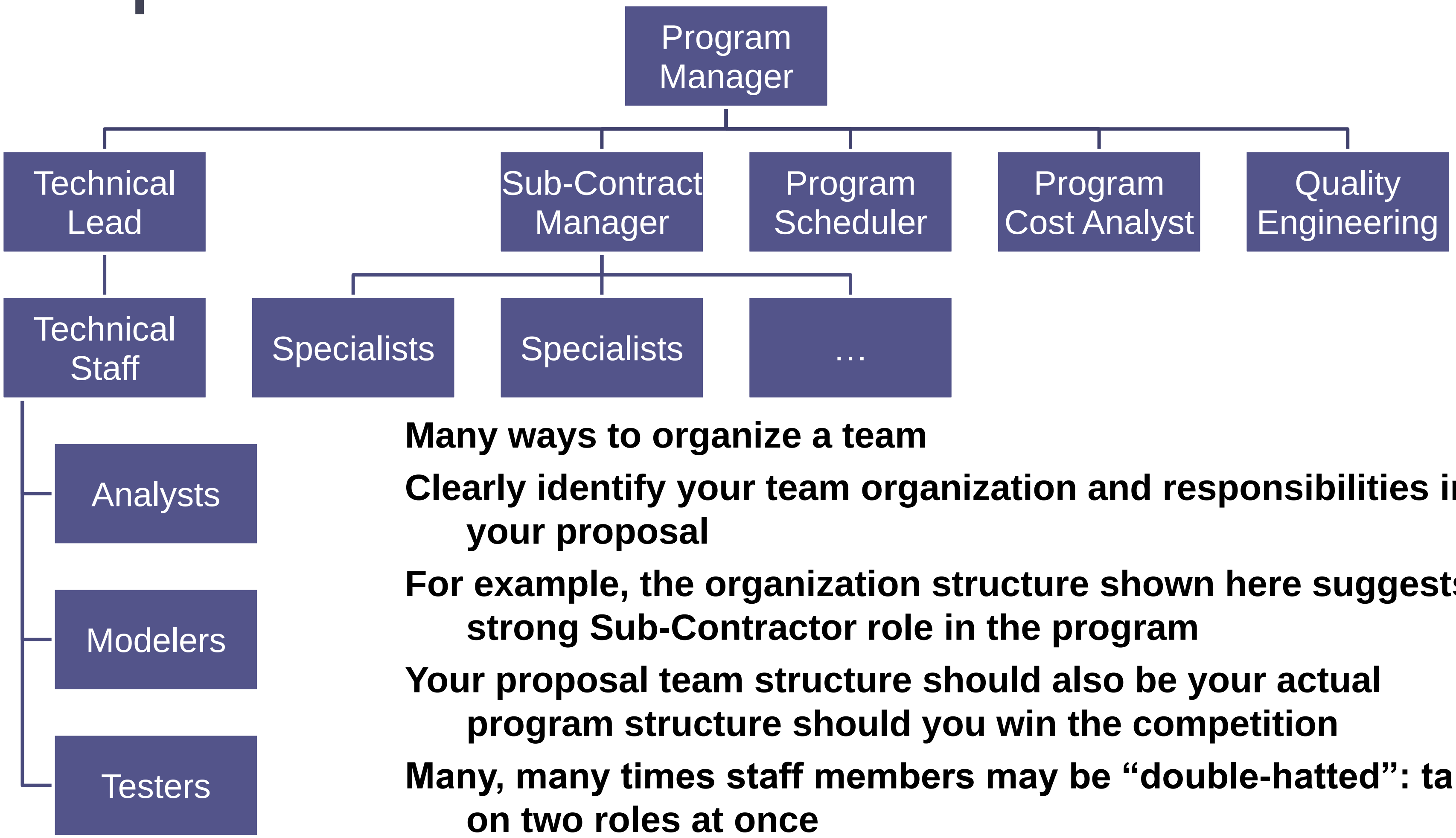
There truly is no “I” in “TEAM”

Show that your Team is integrated and ready to successfully win and prosecute the program

Believe in your approach – never minimize it: if you have doubts, your customer will doubt you as well

DWYSYWD “Do What You Say You Will Do”

Proposal Team



- **Many ways to organize a team**
- **Clearly identify your team organization and responsibilities in your proposal**
- **For example, the organization structure shown here suggests a strong Sub-Contractor role in the program**
- **Your proposal team structure should also be your actual program structure should you win the competition**
- **Many, many times staff members may be "double-hatted": take on two roles at once**

Proposal Credibility

- How do you convey credibility?
  - Show solid modeling capability
  - Demonstrate you have the tools, the fundamental knowledge, and how you intend to apply that to the customer's problem
  - Show prior work that is related
    - Build trade charts showing design trend curves
    - Build trade matrices and tables showing breadth of your trade space
  - Select and analyze a complete design
    - Show you are capable and your staff is ready and able to perform
    - In areas where you are weakest, show that you will increase your expertise by hiring recognized consultants and specialists
- Know your design – know it in and out – so that you can defend its capability
- Know your costs – so that you can defend the cost credibility
- Whatever you don't know, do research on…
  - Google, Encyclopedias, other proposals for similar systems, technical notes from prestigious conferences
- Never admit to a serious weakness in your design – it just shows you haven't done your homework
  - For any unknown performance weakness, show you have options and early-on in the program you will trade and select from these options

Things You Should Put In Your Job-Bag

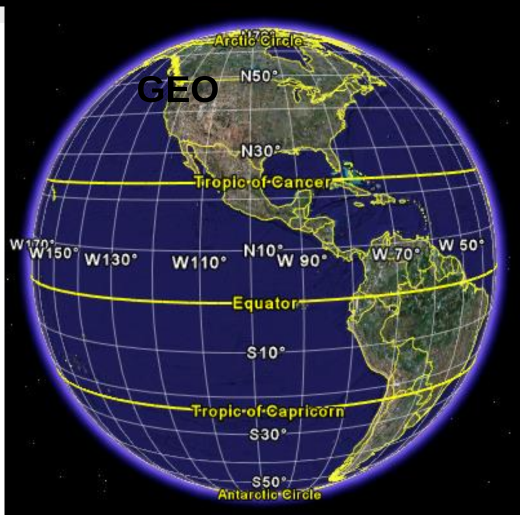
- Know your product
- There is no excuse for not knowing your product – whether pencil or payload
- Every part of your product has a function – know the function of every part
- Remember – we communicate by view graphs – nobody asks for white papers anymore, they say, "Give me 3 charts on that subject…"
  - Your customer will be very tuned-in to view graph language

- Know your "elevator speech"
  - If you were caught in an elevator with Bill Gates know the 5 sentences you would say – after "Hello, sir"
  - More importantly if you were caught in an elevator with the decision maker involved in your system, what is the ONE view graph that you would give him to maximally influence his thought process

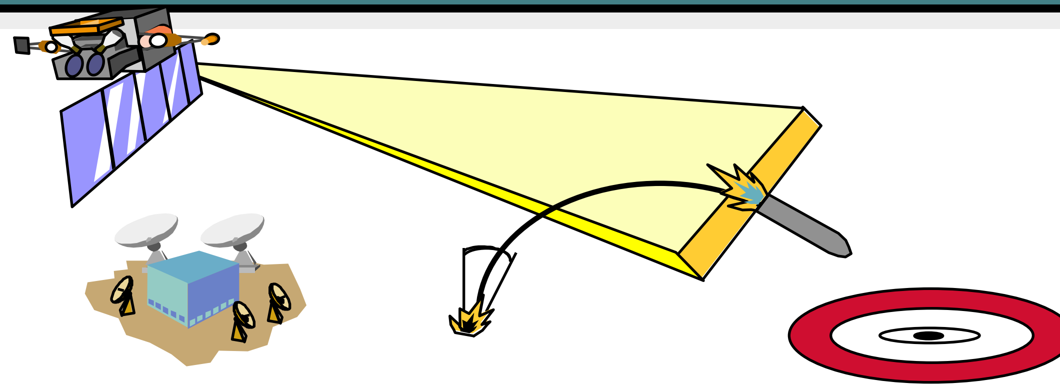
- You should be able to summarize on one chart the essence of your design
  - THAT IS THE CHART YOU GIVE IN THE ELEVATOR

The Elevator Viewgraph

Our Sensor Satisfies All Requirements: Will Be Designed, Built And Tested In 3 Years

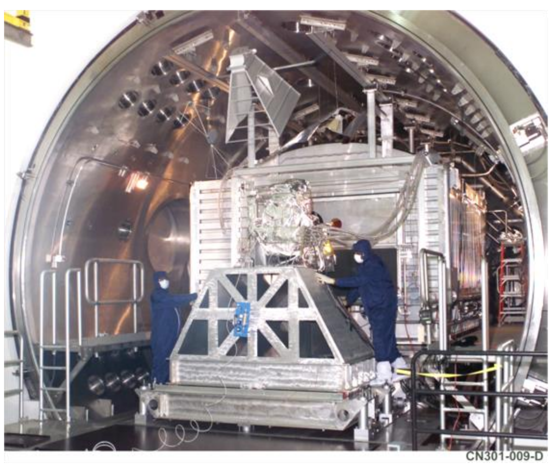


Full Surveillance Coverage



Mission Control Station

Timely communication to the Users 24-7-365



Thorough Test Program

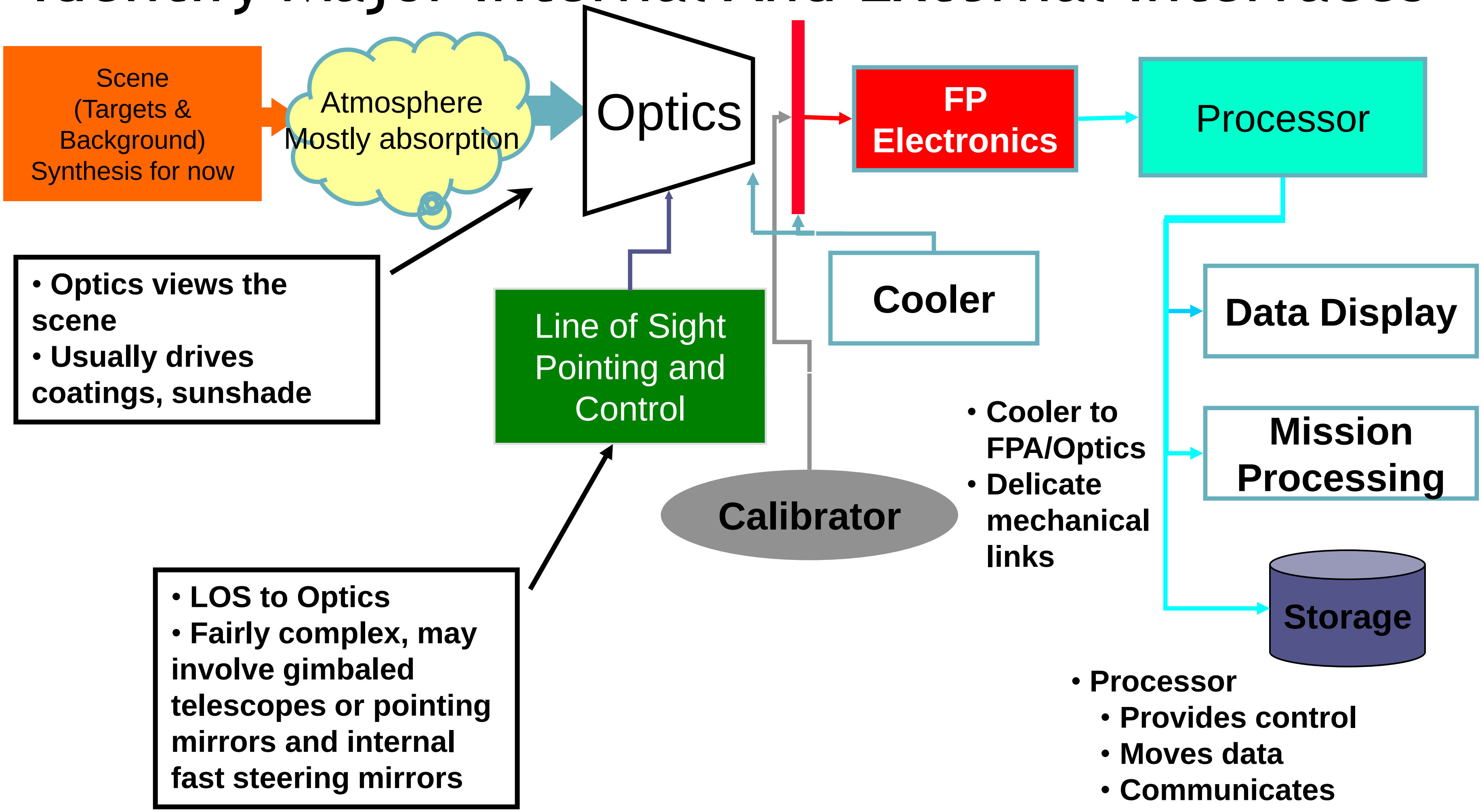
Sensor Targets	Performance
Volcanic Eruptions	√
Lava Flow	√
Forest Fires	√
Oil Fires	√
Large Industrial Facilities	√
Jet Aircraft over water	√
Rockets/Missiles flights & launches	√
High Energy Laser tests	√

Meets All Target Detection Requirements
√ shows positive margin

Terminology

Nomenclature	Definition
Blue Spike	Heuristic manifestation that as you move further away from a hot CO2 emission, it appears to move toward shorter wavelengths
Canonical band	Abundance of water vapor in hot plume has led to the belief that 2.7 to 3µm is a band that is critical to surveillance of any type
CDF	Cumulative Density Function. The integral of the Probability Density Function from –inf to the current value. The normalized Cumulative Density Function will always approach unity.
Channels	A convenient way to separate TDI detectors from pixels
Detector	A physical device – converts light into electrons
Engineers	That incredible group of individuals that bend steel in their mighty hands
FPA	Focal Plane Array – a configuration of detectors near the focus of the optics
GEO	Geosynchronous Equatorial Orbit – stationary above the Earth – actually performs a figure 8
HEO	Highly Elliptical Orbit – Molniya is a good example
LSB	Least Significant Bit – normally set at or just below the NEFD of a system
Microflicks	Radiance in µwatts-cm^{-2}-sr^{-1}-µm^{-1}
NEdT	Noise Equivalent Delta-Temperature. The minimum temperature differential between two bodies of the same size and emissivity that a sensor can discern
NEFD	Noise Equivalent Flux Density: one of several nomenclatures to define a sensor sensitivity
NEI	Detector level noise equivalent irradiance – related to NEFD through optical layout
NET	Noise equivalent target. The synthetic target in the far field that produces a SNR =1
Optics	Collector normally with optical gain: bigger input pupil than at focus
PDF	Probability Density Function. The occurrences of intensity – in our case normally pixel intensity – throughout a set of data – in our case normally an image.
PSF	Point Spread Function. A characteristic function of the optical telescope. Diffraction sets the final limit of performance
Pixel	A logical device – made from the detector signals, but may not have the same spatial, temporal or even spectral resolution as detectors
Principal Plane	Misused by this author – establishes the Fourier Duality
Revisit time	The time between visits of the same survey area.
SCA	Sensor Chip Assembly – a FPA subsystem. More convenient to build a modular approach to FPAs than to populate with detectors and circuitry directly
Strawman design	Concept with some analyses back-up. Usually Strawman design is dismissed on maturing.
Supercolumns	Number of columns of detectors that scan through the same field of view in time sequence. Convenient for TDI.
Target	Any object that is the goal of a surveillance protocol
TDI	Time Delay and Integration. A method of increasing focal plane performance. Pixels are made up of several detector outputs carefully timed and summed.
Threshold	A dynamic signal level, established through some algorithm process, above which the signal exists: below which the signal is set to a no-signal state
Weiner Spectrum	Frequency distribution of a scene – scene clutter characterization

Identify Major Internal And External Interfaces



- Questions