Conclusions

In this paper, we have examined the effect of uncertainty on several classes of space system architectures. These are used as models of engineering systems. We have shown that there are many types of uncertainty. These range from technical uncertainty (does the propulsion system deliver the specified thrust with the specified efficiency) to market based uncertainty (what will be the response of people in London to the space based delivery of T1 links compared to procuring the service through fiber) to policy uncertainty (will the Congress keep funding the development of this system at the same level as last year?).

When these uncertainties are taken into account in the design of these complex space system architectures a number of interesting conclusions follow. The first is that the design points may be quite different with uncertainty incorporated from the beginning as compared to not incorporating the uncertainty. This is clearly seen in the broadband case where the LEO based systems have clear performance advantages over all other systems. Thus Teledesic (& the narrowband Iridium) initially chose LEO. However the uncertainty and in this case risk associated with these systems is so high that the use of GEO based designs, while returning lower performance, is the path that most commercial systems have chosen. More generally, this case illustrates that the best way to consider the design may be to consider portfolios of architectures and carry balanced diverse sets of designs as long as possible.

The second conclusion is that some of the uncertainty is caused by human behavior that is endemic to the nature of the way that stakeholders balance their interests associated with these systems. This was seen in the cost capping analysis of the ionospheric mapper. The likelihood that there will be budget changes in the design and construction of these systems is much larger than the likelihood that they will get exactly what they request. This is due to the dynamic nature of the political process by which decisions are made and policies are decided. Given that it flows from the nature of human behavior, it is a kind of irreducible uncertainty (unlike many types of technical uncertainty). We showed that it was possible to consider this kind of irreducible uncertainty in the design of the system and actually make choices knowing one is subject to this uncertainty.

A third observation flows from consideration of how some of the commercial and military space system architectures have been used in practice. GP S was originally designed for guiding long-range nuclear bombers to their targets (which accounts for the very low power signals). DSP was originally designed for finding strategic ballistic missile launches and relaying information on those launches to the National Command Authority in Washington. The primary civilian use of GPS is now helping hikers not get lost & providing timing signals to cell phone networks while the primary military use is in close air support. DSP is now used primarily to find short-range tactical ballistic missiles and relay those results to forces in theater. Both of these substantially different uses arise from the fact that the original architectures had enough uncertainty in their use (a kind of flexibility) that the interaction with creative humans led to new ways of thinking about and using the systems. This indicates that uncertainty is not a synonym for risk. If the architecture of DSP had been so tightly specified that it could not be used in any other way than finding strategic ballistic missiles then it would have fulfilled it's original mission and be unable to fulfill the subsequent missions (which where not envisioned when it was first flown). In a similar manner, the development of the large commercial market associated with GPS was a complete surprise to the original designers of the architecture but the architecture was robust enough to accommodate this kind of use.

We now generalize to engineering systems and try to draw some analogous conclusions. Thus the three conclusions about uncertainty and engineering systems that flow from this analysis are

1) Engineering Systems must be designed with uncertainty as one of the central organizing principles.
2) Since Engineering Systems have management and social dimensions and thus involve human interactions, there is an irreducible uncertainty associated with these dimensions that will affect the design of the system.
3) Uncertainty in use may allow the engineering system to satisfy quite different missions from the original one. Thus, uncertainty and risk may not be correlated; indeed it is humans interacting with the uncertainty that allows the flexibility to be creatively used.

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