Mar 7th, 8:00 AM

Spacecraft Communications System Design Steps

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Summary

A spacecraft communications system is defined as including not only two-way voice links, but also command channels from the earth, telemetry (and in some cases TV) to the earth, as well as tracking transmitters or transponders. These links have varying significance for the common vehicle phases of launch, orbit (either parking or mission), objective trajectory adjustment and/or return; some of the features of these operational phases are illustrated for their effect on communications.

In the course of designing such communications systems for major spacecraft programs, certain fundamental areas inevitably appear, and lend themselves to a systematic approach. By applying the eight design steps subsequently discussed in the sequence indicated, a logical analysis of the various trade-offs can be made with a minimum of time and effort. These design steps involve the basic mission, number and choice of operating frequencies (including safeguards), radiation pattern coverage (antenna configurations) and duration of operating signal strength margins, and trade-offs between electrical power; thermodynamic, weight, and control dynamics limitations, as well as consideration of the environment, reliability, and availability of equipment to fill the requirements thus defined. Consideration is given to the choice and complexity of possible data to be handled, as well as various transmission techniques.

Introduction

Although most space missions differ from each other in details, a pattern of common problems and considerations for communications and tracking has emerged in the course of designing for a number of major spacecraft programs. This includes manned orbital flights such as the Mercury Project and space stations, as well as space probes such as Apollo. Some fundamental "stepping-stones" appeared, along with a preferred sequence of handling, to avoid needless repetition or iteration.

It will be the purpose of this paper to point our specific areas of consideration, and suggest a sequence of solutions that will minimize overlap or redundancy of calculations. The areas will be kept general enough to have some application to a variety of spacecraft communications problems.

I am taking the term communications to involve not only two-way voice with earth, but also commands up to spacecraft, telemetry back down from the spacecraft (including possible TV), any voice-links with other spacecraft, external crew members, or internal intercom, and last but not least, the space-borne portions of the radar tracking links.

This, then is a good starting point—establishing the links that are needed.

I. Establish Needed Links

These, of course, are largely dictated by the mission. Two-way voice has been predominantly between earth and spacecraft; it will soon be embracing spacecraft-to-spacecraft and between a spacecraft and crewmen outside the mother ship.

Telemetry and command links are of greatest importance during the research phase of a program.

The importance of TV partially depends on how literally one believes in the old adage that "a picture is worth 10,000 words," and the political pressure from the Russian usage of TV.

The significance of radar tracking is again a function of the mission. For orbital passes, radar can be relied upon more than it can be for the greater distances of space probes (e.g. lunar or interplanetary). However, for the latter situation, the necessary equipment for rendezvous or approach altitude above other planets or moons, is taking on increasing significance.

Now we come to one of the points of a preferred sequence in our design steps. Experience has shown that it is preferable...
to make a choice of desired operating frequencies next, since this affects so many other subsequent designs.

II. Make Choice of Optimum Frequency (s)

The factors to be examined that govern the choice of optimum frequency or frequencies should be applied to each of the links in slide 1. These factors are:

II, A. Technical Trade-offs

Technical trade-offs of beam width and orientation (or pointing) accuracies vs. antenna size and gain needed.

Naturally, for a given amount of energy to be radiated, the intensity at a receiving point will be less, if that energy is spread over more space. Thus, a narrow, beamed signal will require less transmitter power and hence less weight, size, electrical power consumption, and less internal generated heat to be dissipated, for a given signal level at the receiving site.

Furthermore, the amount of gain attained in this way is a function of how many electrical wavelengths large the antenna is, which of course reverts back to the frequency chosen. No doubt most of you are already aware of the associated problems this can bring in terms of structural interference of incompatibility, associated with preferred spacecraft orientation based on the mission, plus power and weight required to achieve the necessary degree of pointing accuracy. Trade-off studies here may show that it is better to provide more transmitted power to a lower gain broad-lobed (or omnidirectional) antenna than to provide for necessary movement of, say, a parabolic dish of appropriate size. This is one of the innumerable examples in spacecraft design of the close inter-relationship and team work required of several disciplines; in this case, electronics, electrical power, weights, structures, aerodynamics, etc.

The desirability of flush antennas during launch and re-entry makes them become significant and important to the preliminary structural design of the spacecraft, and is another reason why they should be considered early, and not just stuck on after the structural configuration is finalized. A case in point is the discone antenna of the Mercury capsule. This antenna filled the requirement for a very broad-band pattern all the way around the capsule (also serving to isolate two large areas of metal for H.F. radiation). Final placement of this antenna was partially determined by the undesirability of having it carry the mechanical loads of the main parachute and escape tower across it (it subsequently had just the lesser load of the drogue chute). Even so, in the production phase, a decision was made to strengthen the dielectric window of this antenna with fiberglass ribs as a precaution.

This antenna brings in another consideration - the operational philosophy of the spacecraft. While the intention was to maintain orientation of the Mercury capsule, thus permitting an earth optimized antenna, if the orientation system should fail and if such a directional antenna were in use it would no longer be pointed toward the earth at the very time when high signal level communications with the ground (and possible ground command-control) would be urgently needed. Hence, the decision for essentially omnidirectional coverage.

II. B. Comparison

The next factor would involve a comparison of various attenuations, noise level, distance and pattern to be covered.

As most of you are aware, the free space attenuation increases with frequency, especially at the resonant frequencies of water vapor and oxygen molecules when the atmosphere is included in the path. Of course, increase of atmospheric noise and reduced effective electrical size of the antenna (and hence gain) are constraints in going toward lower frequencies. Needless to say, the best frequency for propagation will vary with the link, and whether it is space-to-space, space-to-earth, or earth-to-space. How much transmission path attenuation can be tolerated is a function of the mission. If the mission calls for orbiting, the orbit height will enter in here, both on path length, and line-of-sight coverage pattern. I will say more on these points, shortly.

II. C. Considerations of future spectrum assignments.

We can't overlook the political aspects of this factor and the one that follows. Most of us have seen the ever-
increasing clamor for spectrum space, and
try to follow the pending assignments of,
for example, the higher frequency tele-
metry bands. Nor is this always in the
future. Those of us that suffered
through the voice frequency assignments
on the Mercury Project, especially the
H.F. voice, can attest to the magnitude
of the problem of finding spectrum space
for equipment already under construction.
Furthermore, the trend to higher frequencies
is of mixed blessing. While the state of
the art is struggling to catch up, the
lower r.f. efficiencies of transmitters
at these frequencies results in trade­
off penalties of more size, weight,
input power, and heat to be dissipated
for a given output, although the antennas
are smaller or have higher gain (at the
expense of beam-width). This behooves
us to keep abreast of the technological
developments such as varactors, parame­
tric amplifiers, and the like.

This brings us to the associated
factor of:

II. D. Facilities in existance for the
given time scale.

Not only am I referring to individual
equipments and the state of the art, but
also the extensive ground range facilities.
When it comes to submitting a proposal on
a competitive award for a mission, some
so-called "Brownie points" can be made
by using as much of the existing ground
complex as possible without compromising
the mission, and thus saving the time
and costs of constructing new specialized
ground stations. Therefore, after the
technically optimum frequency for a link
is obtained, it should be reviewed in
the hard cold light of reality and
availability.

Additionally, after the theoretically
optimum frequency is determined for each
link, a subsequent tie-in should be made
with the trade-offs of one (or a few)
 basic transmitter(s) and frequency, vs.
a separate signal source and different
frequency for each link (as we will
examine later in slide 10). There are
also technical considerations of the
best frequency for particular phases of
a mission as, e.g. the problem of inform­
ation transmission through an ion sheath
associated with a re-entering body.

Before we leave the subject of
frequency, I would like to remind you of
the potential problems of interaction,
if more than one frequency is used.

Besides the basic transmission and recep­
tion frequencies, the sum and difference
products, including modulation and SCO
frequencies, receiver local oscillator,
and even a-c power components, should be
computed and charted, to avoid unforeseen
images. As an unusual example of technical
incompatibility, I would like to hypothe­
size a case that had a real-life counter­
part. Let us assume that our spacecraft
uses two telemetry transmitters, one near
either end of the current 216-260 mc.
band. If these transmitters were simul­
taneously transmitting on, let us say,
230 mc. and 255 mc. respectively, their
beat frequency sum would be 485 mc. This
might give no problem in local check-outs.
But for launching at Cape Canaveral, let
us further hypothesize a range safety
system that emits on a nominal safety
70 mc. Now we could have a resultant beat
frequency difference of 415 mc., which
for illustrative purposes could be taken
to be the command destruct frequency for
the spacecrafts' booster:

Moving on to the next slide (3), we
want to:

III. Establish minimum signal levels

Minimum signal levels and necessary
periods of contact for the links decided
upon in slide 1, may now be established.
The mission sets the distance involved,
and the relative importance of the
particular link being considered (thus
determining the fade margin and safety
margin for tolerable information error
rate). A circuit quality analysis table
would be a convenient way to handle the
main factors. For ease of handling, the
headings could be: (refer to slide 3)
Link of interest; Frequency; Power of
transmitter; Losses: transmitter to
antenna; Gain of transmitting antenna;
Distance; Free Space Loss; Gain:
receiving antenna; Circuit margin; actual
compared to desired.

Additionally, the established mission
and its height will affect the ground
coverage obtained with a given antenna
pattern, and decide whether more ground
stations are needed, or if gaps can be
tolerated in some links of communications
(or whether changes need be made in the
antenna radiation pattern to mitigate
these "outages"). It becomes a matter of
philosophy and doctrine how much of a
"blind spot" or gap in coverage could be
tolerated for, e.g., on Apollo spacecraft
when below 10,000 miles where the present
3 DSIF station coverages cannot converge,
but the spacecraft still at altitudes too great for the Mercury/Gemini, PMR and AMR trackers; present expansion efforts and plans for the world-wide net should alleviate this problem.

IV. Determine the data to be carried.

The data to be carried by the links set in step 1 is the next suggested step in the sequence. Discussion of the details of each link will not fit on one slide (and yet permit you to read it), so this slide will only refer to:

IV. A. The number of quantities to be telemetered (and required accuracy)

Again, the mission must be considered as a guide, and may involve methods for security or secrecy. This must be tempered by the bandwidth and signal power available, and the time and complexity that can be tolerated for encoding.

Principle sources of information of probable interest would come from the categories of:

1. Spacecraft structure such as stresses, deflections and temperatures.
2. Spacecraft operation, including propulsion system and electrical power levels.
3. Operation of the guidance system, whether we are monitoring remote or internal systems, of open or closed-loop, with inertial, celestial, radio/radar, techniques, or a combination thereof.
4. Human factors, which can involve the life-support system parameters, outputs from body sensors, radiation environment, and possible chores to monitor the human occupant's reactions.

In the Mercury project, one telemetry transmitter could be keyed off and on to serve as an emergency non-verbal back-up for the voice channels. This, of course, did not involve any additional channel requirements, but does illustrate another human factor consideration.

5. Outputs of scientific experiments are present to a greater or lesser degree, depending on the mission, but could predominate in the case of test space stations, and should be duly considered.

IV. B. Number of commands

The number of commands to be handled, their required accuracy, and amount of security from interference or unauthorized control, is the subject of the second of the links under consideration.

In the present state of risk of space flight, programs in this country usually start out with unmanned flights which have some built-in time sequenced controls, and some remote controls from ground stations. Mission philosophy then will determine:

1. What is sufficient capacity for unmanned trial flights. Furthermore, there is a growing tendency to allow the human occupants more latitude of decisions and control. The concern prior to Mercury about prolonged weightlessness and so-called "space raptures" is giving way to a "shirtsleeves atmosphere" as in the case of Apollo. The areas where (2) the amount of control by remote command vs. on-board human participation will depend on the prevailing philosophy are:
   a. Guidance (Mercury compared to Gemini and Apollo)
   b. On and off control of various equipments. This could include such equipments as high-powered telemetry or power amplifiers, radar tracking beacon transponders, (or other substantial power consuming items whose operation is desired only when within range of certain ground stations), timing clock resetting signals (in the case of Mercury), and so forth.
   c. Command destruct signals of certain items (or everything), if the range safety or military security situations should require.

I mentioned previously the telegraphy keying of a telemetry transmitter as an alternate path for the voice links from spacecraft to ground. Mercury also had an "extracurricular" voice back-up from ground to spacecraft. This essentially came "for free" over the FRW-2 command transmitter, because the modified DRW-11 receiver relays responded to audio tones
starting above 7500 cps, but both trans-
mitter and receiver would handle a 300-
3000 cps f-m voice channel with ease,
thus giving extra voice reception from
the earth.

IV. C. Number of Voice Links

Continuing with our individual
slides of each of the communication links
initially established, we come to the
number of voice links, and estimates of
their utilization time.

Here again, the mission, by setting
the number of people and how much they
will want (or be allowed) to talk, will
be the guiding criterion.

In the case of Mercury, only one
voice channel was needed, but both HF
and UHF were available for reliability
through redundancy, and according to the
desired coverage philosophy (it also
served as something of a scientific
experiment to see what HF would do, from
a transmitter that far into the iono-
sphere). With nothing better to go on
than fighter pilot experience, the
assumption for Mercury was that the
voice transmitter would be on approxi-
mately 1/10 of the flight time, as an
average. For the subsequent missions of
increased duration including Gemini, this
figure of course has been reduced.

This consideration involved primarily
the first subtopic:

1. Communication between the space-
craft and the ground. Gemini,
Apollo and others also involve
voice communication:

2. Between the basic spacecraft and
resupply, exploratory, or re-entry
and/or rendezvous.

3. Between internal and external
crewmen.

4. Intercom within the spacecraft.

IV. D. Television

Another link that could bear some
consideration is television, and the best
compromise of transmitter power (as it
affects wattage consumption and on-
board heat generated) plus channel band-
width vs. the following:

1. Minimum acceptable signal-to-
noise ratio.

2. Fineness of scanning resolution
(i.e. how many lines of resolu-
tion).

3. Real-time vs. slowed-down video
(from stored scenes). This, of
course, depends on whether rapid
motion is to be viewed rather than
(for example) relatively stationary
instrument and dial readings. The
number of frames per second may
be a trade-off with the preceding
item of resolution, for a given
signal band-width (depending on
the modulation techniques sub-
sequently discussed). The Tiros
weather satellite program is a
good example of compromise, with
roughly 0.1 second of viewing
time, and almost 10 times that
long for slow scan readout,
permitting essentially 500 line
resolution in less than a 70kc
transmission bandwidth. The
Ranger long-scan also showed up
in the partial pictures in
process at the instant of impact
onto the moon.

IV. E. Radar Tracking

Last (but not necessarily least) of
our links under consideration for data
requirements are the radar tracking
requirements, for both earth radars and on-
board rendezvous radars.

The information spectrum required will
be influenced by such self-explanatory
techniques as:

1. Coherent vs. pulse operation

2. Full-time vs. part-time operation
(such as within range of tracking
station only)

3. Accuracies required (as manifested
in the pulse widths and prf).

4. Consideration of the amount of
reliance on radar tracking, vs.
on-board human guidance, including
visual observations, and adjust-
ments. Here we are again, back
to the mission and operational
philosophies. Certainly, they
are closely interrelated and must
be reviewed throughout the
technical planning and engineering
design.

V. Choice of Modulation Technique
The next step in the recommended sequence of spacecraft communications design, is the choice of modulation techniques. Taking the links that were established in slide 1:

A. Voice should be examined for the usage considered in slide 6, against the relative merits and disadvantages of such as Double side band AM, Single side band, compatible single side band, frequency modulation, and even possibly digital voice if secrecy or interplanetary distances are involved.

Even familiar D.S.B. AM, can profit from such refinements as speech clipping. By improving the average power level of intelligible frequencies, such speech clipping in Project Mercury achieved a discernable 5 to 6 db improvement in signal over noise, for 12 to 14 db of speech clipping.

B. For telemetry, the requirements established from slide 4 will determine the quantity and accuracy required, in terms of bits or levels.

This will reflect in such choices as FM/FM, PAM, PCM, PDM, SSB/FM, or various phase-lock techniques.

C. For the command link, slide 5 gave us requirements to be fulfilled. This might involve a possible matrix for simultaneous signals or for security, and such modulation factors using frequency-shift keying or digital techniques will involve consideration of the number of bits, address, and so forth.

D. The possibility of a television link requirement was mentioned previously, and its considerations covered in slide 7. The decisions made at that time concerning picture speed and resolution will now influence the choice of modulation techniques such as digital/PCM, single sideband AM, FM, or FM with feedback.

VI. Number of Units

Now we come to a topic mentioned earlier when we were considering optimum frequencies; do we want individual transmitters and receivers for each link, perhaps on different frequencies, or can overall economy and ease of operation be achieved by one basic transmitter unit? Initially, the optimum frequency for each link can be selected on the basis of individual transmitters. If these frequencies come out to be all the same, this suggests combining. However, they probably won't, but it may be necessary to face the reality of a basic transmission frequency, especially if the equipment is used in an integrated tracking/data system such as the Apollo unified S-band system.

A. It turns out that there is no pronounced saving in space-borne power or weight with a common transmitter, if a broader frequency spectrum is required with multiple SCO's, hence requiring more r.f. power for the S/N. There may be a saving if some links have unused time that would permit time-sharing or multiplexing. A saving can be effected in ground equipment.

B. Another aspect worth considering is the relative reliability of the overall mission to succeed with one transmitter vs. several, and the number of spare or back-up units required to achieve the desired degree of reliability.

In this age of micromodules, integrated circuits, and ultra-compact equipment, consideration should also be given to repairability vs. throw-away units, especially as the philosophy tends to shift (particularly for space flights of long duration) toward in-flight maintenance.

VII. Antennas

Now we can go back to antennas again, and consider the physical configurations of the antennas.

Some thought had to be given to this aspect when the frequency choices were being made, and the entire topic could have been considered sooner, but the information in the steps just covered influences the final design, so earlier "firm" decisions would have to be done over. Thus, actual antenna designs can now be made to:
A. Cover the frequency or frequencies and radiation patterns chosen from the factors of slide 2;

B. Provide the gain to fulfill the signal level requirements computed by slide 3, by means of the transmitter power levels established in slide 10. This may have to be an iterative process between antenna size and transmitter power, and acceptable signal level, but now it is more meaningful than it would have been earlier, when there were more variables or unknowns.

C. Endure the physical stresses associated with each pertinent phase of the particular mission. For example, the (1) launch phase would have its vibration, g-forces, and possible aerodynamic heating; (2) operation in space would have the extreme cold and problems of friction of any moving surfaces, plus other environment-induced problems from the vacuum, radiation, and micrometeorites; (3) any spacecraft modules for entry into our own, or some other atmosphere must contend with the problems of heat, ion sheath, and g-forces.

D. Be compatible with vehicle structure. This could involve disruption of structural members of flush antennas, or possible shading of sensors by external "big dishes" and compatible with vehicle orientations. For directional antennas to look at the earth, consideration (and probable compromises) must be made if the spacecraft is sun-, moon-, or planet-oriented. Particular guidance maneuvers or mid-course corrections could be a problem in this area. If rotation is contemplated, perhaps for artificial gravity in a space station, this can affect the selection of antennas severely.

In conclusion, we may now have a system that has been optimized from the communications point of view, but the other disciplines must also be reconciled.

VIII. Comparison of Trade-Offs

A. The reliability people may take exception (e.g.) to the life of the magnetron in the radar transponder, or some antenna change-over switches, or the complexity of a decoding matrix in the command receivers, and so on.

B. The electrical group may have figured on adequate battery watt-hours by using their nominal 28 volt source between 30 volts initially, to an end-point of 18 volts. This, of course, plays havoc with equipment design, and is conducive to power-hungry voltage regulators. This promptly runs up the wattage requirements beyond the original communications estimates.

C. The weights group is notorious for brow-beating other groups to minimum figures. As inevitable growth and/or philosophy changes of equipment requirements take place and increase the weight, the communication engineer must major in diplomacy along with his engineering.

D. Cost is shown as last, but is by no means least. Space work is expensive, and in areas of the unknown, CPFF has frequently been the only logical approach, but even the design engineers must be cost-conscious since there is an increasing tendency toward fixed-price or incentive contracts.

Finally, I would like to say that the foregoing are based on actual experiences in some prominent space programs, and are not figments of the imagination.
I. ESTABLISH NEEDED LINKS.

Slide 1: Links Involved in Discussion

II. MAKE CHOICE OF OPTIMUM FREQUENCY(S)

A. Trade-offs of Beamwidth and Orientation (pointing) vs. Antenna Size and Gain Needed.
B. Comparison of Attenuations, Noise Level, Distance and Pattern to be Covered.
C. Possible Future Spectrum Assignments.
D. Facilities in Existence for the Given Time Scale.

Slide 2: Choosing Optimum Frequency (s)
III. ESTABLISH MINIMUM SIGNAL LEVELS AND NECESSARY PERIODS OF CONTACT FOR THE LINKS DECIDED UPON IN SLIDE 1.

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**Suggested Format**

Slide 3: Format for Establishing Minimum Signal Levels

**IV. DETERMINE DATA TO BE CARRIED BY LINKS OF STEP 1.**

A. No. of Quantities for T/M, and Required Accuracy.

1. Spacecraft Structure.
   (including thermal)

2. Spacecraft Operation
   (incl. propuls. & electrical)

3. Guidance

4. Human Factors

5. Scientific Experiments

Slide 4: Data to be Transmitted:

Telemetry

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IV. (con't.)

B. Number of Commands; Accuracy & Security.

1. Sufficient Capacity for Unmanned Trial Flights.

2. According to Extent of Human Participation,
   a. Guidance system signals.
   b. Equipment on-and-off instructions.
   c. Destruct if necessary.

3. Possible Voice Link Back-up.

Slide 5: Data to be Received:

Commands
IV. (cont.)

C. Number of Voice Links and Estimate of Utilization Time:
1. Between Spacecraft and Ground.
2. Between Basic s/c and Re-supply or Re-entry Vehicles.
3. Between Internal and External Crewman.
4. Intercom Within the Spacecraft.

Slide 6: Data to be Handled:
Voice links

IV. (cont.)

D. Trade-off TV Xmtr. Power and Bandwidth vs:
2. Fineness of Scanning Resolution.
3. Real-time Video vs. Slowed-down Video. (scanning rates)

Slide 7: Data to be Handled:
Television

IV. (cont.)

E. Radar Tracking Requirements, Earth and Rendezvous:
1. Coherent vs. Pulse.
2. Full-time vs. Part-time Operation.
3. Accuracies Required.
4. Degree of Reliance on Radar Tracking vs. On-board Human Guidance.

Slide 8: Data to be Handled:
Radar tracking and Rendezvous
V. DETERMINE OPTIMUM MODULATION TECHNIQUES FOR:

A. Voice
B. Telemetry
C. Command Link
D. Possible TV Link

Slide 9: Modulation Needs

VI. TRADE-OFFS OF NO. OF TRANSMITTERS AND POWER LEVELS.

A. Total Input Power for 1 Transmitter with SCO's for the Various Signals vs. Individual Optimized Xmtrs for Each.

B. Reliability Aspects, Including No. of Redundant or Spare Units for Single vs. Multiple Transmitters, Including Ease of Maintenance and Possible In-flight Repairs.

Slide 10: Choosing Quantity and Quality of Transmitters.
VII. ANTENNA PHYSICAL CONFIGURATION DECISIONS.
A. Cover the Frequency(s) and Radiation Pattern Chosen.
B. Provide Gain to give Signal Levels Chosen, with Transmitter Power Permitted.
C. Endure the Physical Stresses of Various Mission Phases.
   1. Launch.
   2. Space.
   3. Possible Re-entry.
D. Be Compatible with Vehicle Structure, Orientation, Possible Rotation.

Slide 11: Antenna Physical Decisions

VIII. COMPARE FINAL SYSTEM AND SUBSYSTEM TRADE-OFFS IN TERMS OF:
A. Reliability.
B. Power Consumption.
C. Weight.
D. Cost.

Slide 12: Final Comparison of Trade-offs.