Spacecraft Telecommunications System Mass Estimates

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Mass is the most important limiting parameter for present-day planetary spacecraft design. In fact, the entire spacecraft design can be characterized by mass. The more efficient the design of a spacecraft, the less mass will be required. The communications system is an essential and integral part of planetary spacecraft. In this article, a study is presented of the mass attributable to the communications system for spacecraft designs used in recent missions in an attempt to help guide future design considerations and research-and-development efforts.

The basic approach is to examine the spacecraft by subsystem and allocate a portion of each subsystem to telecommunications. Conceptually, this is to divide the spacecraft into two parts, telecommunications and non-telecommunications. In this way, it is clear what the mass attributable to the communications system is.

The percentage of mass is calculated using the actual masses of the spacecraft parts, except in the case of CRAF. In that case, estimated masses are used since the spacecraft has not been built. The results show that the portion of the spacecraft attributable to telecommunications is substantial. The mass fraction for Voyager, Galileo, and CRAF (Mariner Mark II) is 34 percent, 19 percent, and 18 percent, respectively. The large reduction of telecommunications mass from Voyager to Galileo is mainly due to the use of a deployable antenna instead of the solid antenna on Voyager.

I. Statement of the Problem

The task at hand is to separate the spacecraft into two parts: telecommunications and non-telecommunications. The Voyager spacecraft, for example, is made up of the 25 subsystems listed in Table 3.[1] Normally, the Radio Frequency Subsystem (RFS), the Modulation/Demodulation Subsystem (MDS), and the S/X-Band Antenna Subsystem (SXA) are said to compose the telecommunications system, i.e., the communications system between the spacecraft and ground station. However, portions of many of the other subsystems are directly related or necessary to the support and function of these three subsystems. Therefore, a method must be created that will take those related portions of the other subsystems into account.

II. Analysis

The Voyager spacecraft is used here to illustrate the analysis. This method will be used to obtain results for the other spacecraft. We have already done so for the three chronologi-

[1] *Mariner Jupiter/Saturn 1977*, Project Document 618-205, Functional Requirements Book, vols. 1 and 2 (internal document), Jet Propulsion Laboratory, Pasadena, California, 1977.

cally representative spacecraft Voyager, Galileo, and CRAF. To obtain overall percentages, each subsystem is analyzed individually. However, the same method of analysis cannot be used on all the subsystems. The detailed Voyager weight list is used for this calculation.[2]

A subjective analysis of the Voyager spacecraft telecommunications system mass was previously conducted by R. M. Dickinson.[3] This resulted in a figure of fully one-third of the spacecraft mass. The present qualitative analysis, resulting in a figure of 34 percent, concurs with and verifies this conclusion.

The Radio Frequency Subsystem (RFS), Modulation/Demodulation Subsystem (MDS), and S/X-Band Antenna Subsystem (SXA) are the three telecommunications subsystems; therefore all (100 percent) of their mass is allocated to telecommunications.

The ten Science Instruments Subsystems (SCIs) are used for the purpose of gathering scientific data. This is clearly non-telecommunications, so none of the mass is allocated to telecommunications.

The Pyrotechnic Subsystem (PYRO) and the Systems Assembly Hardware (SAH) are clearly non-telecommunications, so none of the mass is allocated to telecommunications. The PYRO subsystem effects the launch vehicle/spacecraft separation, deployed booms, etc., while the SAH subsystem consists of parts needed to assemble the spacecraft.

The Flight Data Subsystem (FDS), Computer Command Subsystem (CCS), and Attitude and Articulation Control Subsystem (AACS) are the three on-board computers. Since these cannot really be broken into parts, the mass estimate is based on how much computing power was devoted to telecommunications. An estimate given by G. W. Garrison[4] was approximately 10 percent of FDS, approximately 10 percent of CCS, and less than 5 percent of AACS. The total FDS mass (19.32 kg) includes the Reed–Solomon coder hardware (2.35 kg). This is considered to be telecommunications mass. Thus, 100 percent of 2.35 kg plus 10 percent of 16.97 kg (the total mass less the RS coder) yields 4.05 kg, or 20.95 percent of the FDS mass allocated to telecommunications. Ten percent of the CCS mass and 5 percent of the AACS mass is allocated to telecommunications.

The Data Storage Subsystem (DSS) is the tape recorder and basically serves as a time buffer and provides functional redundancy for the telecommunications system. Since it wholly supports the telecommunications system, all (100 percent) is allocated to telecommunications.

The Structure Subsystem (STRU), Cabling Subsystem (CABL), Temperature Control Subsystem (TEMP), and Mechanical Devices Subsystem (DEV) are handled differently. For these four subsystems, the detailed equipment mass list is examined (see footnote 2), and each item is sorted into the categories of fully telecommunication, fully non-telecommunication, and partly telecommunication. The "partly telecommunication" category is further subdivided into six categories: PWR (Power), CCS, FDS, AACS, PROP (Propulsion), and DSS, depending on which subsystem they are related to. Fully telecommunication includes any items related to the RFS, MDS, and SXA subsystems, such as the High Gain Antenna (HGA). Fully non-telecommunication includes those items related to the SCI subsystems such as the scan platform and magnetometer boom. This category also contains such miscellaneous items as the phonograph record.

For each of the four subsystems, a percentage of the mass in each of the eight categories is taken and then summed together. One hundred percent is taken for fully telecommunication, 0 percent for fully non-telecommunication, and for the partly telecommunication categories, 10 percent of CCS and FDS, 5 percent of AACS, and 100 percent of DSS. The percentage for PWR (40 percent for Voyager) is taken to be the percentage of telecommunication power as derived in Appendix A. The percentage for PROP is taken to be the percentage of telecommunication mass (34 percent for Voyager) since almost all of the propellant is allocated to trajectory correction maneuvers. Only a very small percentage of the propellant (0.5 percent in the case of Galileo) is allocated to keeping the High Gain Antenna pointed toward the Earth (because of a different engine design, this may be more significant for CRAF). To illustrate, see Table 1 for the calculation of STRU. The complete mass calculation is shown in Table 4. The results of the Voyager mass calculation can be seen in Table 2.

III. Results and Conclusions

We have examined the mass of the telecommunications systems of three representative spacecraft: Voyager, which has been in flight since 1977; Galileo, which is ready to be launched; and CRAF, which is under design. These show the progression chronologically. Due to different mission require-

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[2] J. M. Brayshaw, detailed weight tabulation computer printout (internal document), Jet Propulsion Laboratory, Pasadena, California, August 18, 1977.

[3] R. M. Dickinson, interoffice memorandum to E. C. Posner, IOM 860326 (internal document), Jet Propulsion Laboratory, Pasadena, California, March 31, 1986.

[4] G. W. Garrison, private communication, Jet Propulsion Laboratory, Pasadena, California, July 14, 1986.

ments, certain features of the spacecraft make direct comparison of percentage figures difficult. The most significant feature is that of the differences between the three propulsion systems. The propulsion subsystem of the Voyager mission module is only 35.26 kg. The main provider of propulsion, the propulsion module (158.55 kg), is jettisoned en route. Galileo, in contrast, has a very large retro-propulsion module (201.52 kg) included in the mission module.[5,6] CRAF has an even heavier retro-propulsion module (374.73 kg) compared to Galileo.[7] Other significant features are the spin-bearing assembly and probe-related hardware on board Galileo.

[5] *Galileo*, Project Document 625-205, Functional Requirements Book, vols. 1 and 2 (internal document), Jet Propulsion Laboratory, Pasadena, California, 1982.

[6] *Galileo Quarterly Mass Report and Equipment List*, issue 31 (internal document), Jet Propulsion Laboratory, Pasadena, California, April 29, 1986.

[7] *Mariner Mark II Configuration, Mass and Power Report*, issue 12 (internal document), Jet Propulsion Laboratory, Pasadena, California, August 18, 1986.

However, the present analysis approach is consistent throughout. It is felt that estimates of spacecraft mass are all within 5 percent error. In any case, the results give a fair comparison of mass among the three spacecraft studied.

The results show that the portion of the spacecraft attributable to telecommunications is substantial. In particular, the mass fraction for the three chronologically representative spacecraft, Voyager, Galileo, and CRAF, is 34 percent, 19 percent, and 18 percent, respectively. The large reduction of telecommunications mass from Voyager to Galileo is mainly due to the use of a deployable antenna instead of the solid antenna on Voyager.

We conclude that we should work toward further reducing the spacecraft telecommunications mass. Alternately, we can improve the telecommunications capability of the Deep Space Network (DSN) so that the required spacecraft telecommunications system mass can be reduced for equivalent communications performance. Continued progress in the area of deep space telecommunications technology development is essential to achieving new goals in space exploration.

Table 1. Telecommunications mass calculation for STRU

Category	Mass, kg	Contribution, %	Mass, %
Fully telecommunication	63.16	100.00	63.16
Non-telecommunication	42.10	0.00	0.00
Partly telecommunication			
PWR	21.16	39.64	8.39
CCS	5.22	10.00	0.52
FDS	5.34	10.00	0.53
AACS	11.30	5.00	0.57
PROP	15.38	33.71	5.19
DSS	5.24	100.00	5.24
Total	168.63 kg		83.60 kg

Table 2. Voyager mass results summary

Subsystem	Total mass, kg	TC-related mass, kg	Non-TC mass, kg	TC-related percentage
STRU	168.63	83.32	85.31	49.41
RFS	44.44	44.44	0.00	100.00
MDS	8.41	8.41	0.00	100.00
PWR	136.39	54.07	82.32	39.64
CCS	15.51	1.55	13.96	10.00
FDS	19.32	4.05	15.27	20.95
AACS	49.74	2.49	47.25	5.00
PYRO	5.34	0.00	5.34	0.00
CABL	51.62	8.58	43.04	16.62
PROP	35.26	11.89	23.37	33.71
TEMP	29.63	6.31	23.32	21.29
DEV	16.12	1.29	14.83	8.02
DSS	15.15	14.39	0.76	95.00
SXA	5.09	5.09	0.00	100.00
SCI	123.00	0.00	123.00	0.00
SAH	5.68	0.00	5.68	0.00
Total	729.33	245.88	483.45	33.71

Table 3. Acronyms and abbreviations

Voyager Mission Module Subsystems:	
RFS	Radio Frequency Subsystem
MDS	Modulation/Demodulation Subsystem
SXA	S/X-Band Antenna Subsystem
CCS	Computer Command Subsystem
FDS	Flight Data Subsystem
AACS	Attitude and Articulation Control Subsystem
STRU	Structure Subsystem
CABL	Cabling Subsystem
TEMP	Temperature Control Subsystem
PWR	Power Subsystem
PROP	Propulsion Subsystem
DSS	Data Storage Subsystem
PYRO	Pyrotechnic Subsystem
DEV	Mechanical Devices Subsystem
SAH	Systems Assembly Hardware
SCI	
CRS	Cosmic Ray Subsystem
PRA	Planetary Radio Astronomy Subsystem
PWS	Plasma Wave Subsystem
LECP	Low Energy Charged Particle Subsystem
PPS	Photopolarimeter Subsystem
PLA	Plasma Subsystem
UVS	Ultraviolet Spectrometer Subsystem
MAG	Magnetometer Subsystem
ISS	Image Science Subsystem
IRIS	Infrared Interferometer Spectrometer and Radiometer Subsystem
Miscellaneous Acronyms and Abbreviations:	
CRAF	Comet Rendezvous Asteroid Flyby
TC	Telecommunications
DSN	Deep Space Network

Table 4. Voyager mass calculation

Subsystem		TC-related 100.0%	Non-TC 0.0%	PWR* 39.64%	CCS 10.0%	FDS 10.0%	AACS 5.0%	PROP 33.71%	DSS 100.0%	Subsystem total	TC-related total
STRU	Total	63.16	42.10	21.16	5.22	5.34	11.30	15.38	5.24	168.63	
	TC related	63.16	0	8.39	0.52	0.53	0.57	5.19	5.24		83.56
RFS	Total	44.44	0	0	0	0	0	0	0	44.44	
	TC related	44.44	0	0	0	0	0	0	0		44.44
MDS	Total	8.41	0	0	0	0	0	0	0	8.41	
	TC related	8.41	0	0	0	0	0	0	0		8.41
PWR	Total	0	0	136.39	0	0	0	0	0	136.39	
	TC related	0	0	54.07	0	0	0	0	0		54.07
CCS	Total	0	0	0	15.51	0	0	0	0	15.51	
	TC related	0	0	0	1.55	0	0	0	0		1.55
FDS	Total	2.35	0	0	0	16.97	0	0	0	19.32	
	TC related	2.35	0	0	0	1.70	0	0	0		4.05
AACS	Total	0	0	0	0	0	49.74	0	0	49.74	
	TC related	0	0	0	0	0	2.49	0	0		2.49
PYRO	Total	0	5.34	0	0	0	0	0	0	5.34	
	TC related	0	0	0	0	0	0	0	0		0
CABL	Total	2.47	25.64	6.09	2.07	5.03	2.86	6.93	0.53	51.62	
	TC related	2.47	0	2.42	0.21	0.50	0.14	2.34	0.50		8.58
PROP	Total	0	0	0	0	0	0	35.26	0	35.26	
	TC related	0	0	0	0	0	0	11.89	0		11.89
TEMP	Total	2.48	13.78	2.55	1.09	1.09	4.87	2.00	1.77	29.63	
	TC related	2.48	0	1.01	0.11	0.11	0.24	0.68	1.68		6.31
DEV	Total	0	12.86	3.26	0	0	0	0	0	16.12	
	TC related	0	0	1.29	0	0	0	0	0		1.29
DSS	Total	0	0	0	0	0	0	0	15.15	15.15	
	TC related	0	0	0	0	0	0	0	14.39		14.39
SXA	Total	5.09	0	0	0	0	0	0	0	5.09	
	TC related	5.09	0	0	0	0	0	0	0		5.09
SCI	Total	0	123.00	0	0	0	0	0	0	123.00	
	TC related	0	0	0	0	0	0	0	0		0
SAH	Total	0	5.68	0	0	0	0	0	0	5.68	
	TC related	0	0	0	0	0	0	0	0		0
Total										729.33 kg	246.14 kg

*Also see table in Appendix A.

Appendix A
Spacecraft Telecommunications System Power Estimates

Power is also an important limiting parameter for present-day planetary spacecraft design. A study of the power attributed to the communications system for spacecraft designs used in recent missions is presented here.[8-11]

The basic approach is similar to that of the mass study, i.e., to examine the spacecraft by subsystem and allocate a portion of each subsystem to telecommunications. The percentage for power is calculated using power allocations derived from actual preflight subsystem testing (except in the case of CRAF, which is done using estimates). Only the dry mission module is taken into account. The portion of power for Voyager, Galileo, and CRAF attributable to the telecommunications system is 40 percent, 29 percent, and 18 percent, respectively. The results show that the portion of the spacecraft power attributable to telecommunications is substantial.

The task at hand is to separate the spacecraft into two parts, telecommunications and non-telecommunications, with regard to power. Again, the Voyager spacecraft is used to illustrate the analysis. This method is used to obtain results for the other spacecraft.

The telecommunication-related power percentage is calculated using figures from volume 1 of Project Document 618-205.[8] These list 50 power modes. from launch through the Saturn encounter, with power allocations by subassembly and subsystem. Of the 50 modes, nine are identified as the main power modes, i.e., essentially the cruise background modes and any modes lasting more than two days. The figures from these nine modes are used for the Voyager power calculation and are summarized in Table A-1. Included in Table A-2 are the equations used to calculate the percentage of telecommunication-related power from each of the nine modes. The percentage of telecommunication-related power is extracted from each mode in a manner similar to the mass calculation. The telecommunication percentage for each mode is multiplied by the length of its respective mode and then summed. This sum is divided by the sum of the lengths of the modes to give an overall percentage.

The power figures from volume 1 of Project Document 618-205[8] represent the maximum steady-state power allocated to spacecraft subsystems.

The lengths of the modes are derived from volumes 1 and 2 of Project Document 618-205[8,9] using launch, Jupiter encounter, and Saturn encounter dates from the Voyager 2 mission (see Table A-1).

The power-needed calculation uses the Total DC Bus Power, which is the amount of power the subsystems will be using. The other percentage given is the power available using the net power capability (Most Probable) instead of Total DC Bus Power. Power available is slightly higher than power needed to provide a safe power margin. Therefore this gives a smaller overall percentage.

The mass analysis is done using both the power-needed and the power-available figures. The resulting telecommunications mass percentages are within 1 percent of each other, so only the power-needed figure was used in the preceding mass calculation.

Despite differences in the spacecraft, this analysis approach is consistent throughout. The present estimates of spacecraft power are all felt to be within 5 percent error. In any case, the results give a fair comparison of power among the three spacecraft studied.

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[8] *Mariner Jupiter/Saturn 1977*, Project Document 618-205, vol. 1 (internal document), Jet Propulsion Laboratory, Pasadena, California, pp. 11-23, June 8, 1977.

[9] *Mariner Jupiter/Saturn 1977*, Project Document 618-205, vol. 2 (internal document), Jet Propulsion Laboratory, Pasadena, California, May 12, 1977.

[10] *Galileo Quarterly Power Report*, issue 33 (internal document), Jet Propulsion Laboratory, Pasadena, California, May 20, 1986.

[11] *Comet Rendezvous Asteroid Flyby*, Project Document 699-100, Rev. C (JPL D-1457 Rev. B) (internal document), Jet Propulsion Laboratory, Pasadena, California, May 1986.

Table A-1. Voyager power results summary

Mode number	Length, days	TC percentage of power	
		Power needed	Power available
24	96	46.97	45.31
25	541	38.70	33.20
27	6	39.31	35.56
31	40	45.28	47.32
36	39	45.75	44.73
37	700	38.62	34.44
39	8	33.90	29.35
43	29	45.28	49.50
48	29	37.69	37.89
Total		39.64	35.64

Table A-2. Power calculation equations

Category	Percentage
TC	100
PWR	39
CCS	10
FDS	10
AACS	5
PYRO	0
DSS	95
SCI	0
PROP	33

$$A = (MDS \times TC\%) + (PWR \times PWR\%) + (CCS \times CCS\%) + (FDS \times FDS\%) + (AACS \times AACS\%) + (PYRO \times PYRO\%) + (DSS \times DSS\%) + (STRU^*) + (PROP \times PROP\%) + (SCI \times SCI\%)$$

where $STRU^* = (\text{Bay 1 heater} \times TC\%) + (\text{Bay 2 heater} \times DSS\%) + (\text{Bay 6 heater} \times AACS\%)$

$$B = \text{AC wiring loss} \times \frac{A}{\text{total eng load} + SCI}$$

$$C = (\text{2.4 kHz inv loss} \ldots + \text{power factor loss}) \times \frac{(A + B)}{\text{total 2.4 kHz inv load}}$$

Total TC AC power load = A + B + C

$$D = (RFS \times TC\%) + (PWR \times PWR\%) + (FDS \times FDS\%) + (AACS \times AACS\%) + (SCI \times SCI\%) + (TC/S \times SCI\%) + (TC/E^*)$$

where $TC/E^* = (\text{Az Act Rep} \times SCI\%) + (\text{Sun Sen Htr} \times AACS\%) + (\text{IPU Valve Htr} \times PROP\%) + (\text{IPU Red V Htr} \times PROP\%) + (\text{IPU Thrus Htr} \times PROP\%) + (\text{TCAPU Red Htr} \times PROP\%) + (\text{Scn Pltfm Htr} \times SCI\%)$

$$E = \text{DC wiring loss} \times \frac{D}{\text{total reg DC load}}$$

Total TC DC power load = D + E

$$\text{TC power \%} = \frac{\text{total TC AC power load} + \text{total TC DC power load}}{\text{total DC bus power}}$$