COMPARISON OF RECENT SCOUT CLASS SPACECRAFT SUBSYSTEM WEIGHTS FOR FUTURE WEIGHT ESTIMATION PURPOSES

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ABSTRACT

The purpose of this paper is to compare the subsystem weights of four recently built Scout class satellites to determine if there are any trends which can be used in future weight predictions. The four satellites whose weights are being compared are: MAGSAT, AMPTE, NOVA III, and Polar BEAR. These four spacecraft are different in many areas and were chosen as such, so as not to bias the data.

In order to systematically compare the subsystem weights and extend the results to future spacecraft, a weight accounting system is developed. Thirteen subsystems are baselined. The specific pieces of hardware that are assigned to each subsystem category are defined.

The components of each subsystem of each of the four spacecraft are defined and compared in terms of weight, capability, redundancy, etc. Weight trends are discussed where appropriate.

Subsystem weights vary as one might expect with capability, redundancy, experiment and mission requirements, and launch vehicle imposed constraints. In spite of the major differences in the four spacecraft whose weights are compared, several trends and rules of thumb are developed which can be used in future weight predictions at the conceptual design level.

INTRODUCTION

The purpose of this paper is to compare the subsystem weights of several recently built satellites (of about the Scout weight class) to determine if there are any trends at the subsystem level which can be used in future weight predictions. The criteria used for selecting which spacecraft to include in the study were: it had to have been in the Scout weight class, have detailed information on the individual piece weights, the mission requirements, and the capabilities of the hardware, and, that there be little or no correlation among the subsystem designs. Four satellites were chosen for the study, MAGSAT, the AMPTE Charge Composition Explorer, and Polar BEAR, designed and built at APL, and NOVA III, which was built by RCA. The AMPTE Charge Composition Explorer (hereafter called AMPTE), was launched on a Delta rocket but was included since it falls in the upper end of the Scout weight class.

The four satellites chosen were very different. The total weights varied from 260 lbs for Polar BEAR to 510 lbs for AMPTE. There were two gravity gradient, one three axis active, and one spinning attitude control system. The orbital average powers varied from 28 to 120 watts. NOVA III had an Orbit Adjust Transfer System (OATS) and AMPTE an Inclination Adjust Rocket (IAR). The other two did not carry any onboard propulsion. Two out of the four had tape recorders. NOVA had the Disturbance Compensation System. MAGSAT had a 13 arcsecond spacecraft attitude determination requirement while the other three required ~ ±1°. Three of the orbits were polar, varying from 352 x 578 km for MAGSAT to 1185 km circular for NOVA while AMPTE had a highly elliptical, equatorial orbit. In spite of these differences, some interesting trends regarding subsystem weights were observed which can be used in future weight estimates at the conceptual design level.

WEIGHT ACCOUNTING SYSTEM

A weight accounting system defines the number of subsystems and which pieces of hardware are assigned to each. Thirteen subsystems, listed in Table 1, are defined as part of the study. A summary of the hardware components included in each is given in the sections which address each of the individual subsystems.

Table 1
LIST OF SATELLITE SUBSYSTEMS

Power	RF	Harness
Telemetry	Thermal	Structure
Command	Coarse Attitude C & D	Vehicle Interface
Data Storage	Fine Attitude C & D	Propulsion
		Experiments

There are three reasons for defining a weight accounting system. First, the latest weight reports for each of the four S/C, from which the weight data were obtained, each used a slightly different accounting system. A single system had to be defined before an accurate comparison could be made. An example of this is the yo-yo despin device which was included as part of the Vehicle Interface subsystem on MAGSAT but was part of the attitude control subsystem on Polar Bear.

Second, certain items, because of the way in which they were used, could be allocated to more than one subsystem. Which one they were allocated to had to be defined. An example of this is the fuel tank on NOVA which was used as the gravity gradient boom end mass. This was allocated to the attitude rather than the propulsion subsystem.

Finally, subsystems can be defined such that more realistic comparisons can be made. For example, it was not realistic to compare the attitude determination subsystem of NOVA which had a ± 1°, three axis specification, to that of MAGSAT which had a 13 arcsecond specification. To account for this, the attitude function was split into two subsystems: coarse and fine attitude control and determination.

SPACECRAFT SUBSYSTEMS

Table 2 summarizes the weights by subsystem. In order to more readily understand the differences, further information about each of the subsystem components, capabilities, etc., is provided. For example, much of the weight difference between the AMPTE and the Polar BEAR TLM subsystems can be explained by understanding the differences in the number of housekeeping channels, digital serial interfaces, the amount of redundancy, etc. between the two subsystems.

Each subsystem is discussed in detail in the remainder of the section. General rules of thumb for weight estimation are developed where applicable.

Table 2
SUBSYSTEM WEIGHT SUMMARY (LBS)

Subsystem	MAGSAT	AMPTE	NOVA	Polar BEAR
Power	50.32	65.21	73.81	59.28
Telemetry	12.12	11.61	4.73	4.51
Command	11.92	20.93	9.83	3.40
Data Storage	35.10	25.20	-	-
RF	19.44	19.78	16.01	10.75
Thermal	18.90	12.43	5.19	6.64
Coarse Attitude C & D	39.58	37.94	49.62	27.47
Fine Attitude C & D	50.54	-	30.09	-
Harness	26.53	36.22	23.41	19.60
Structure	66.31	59.31	54.61	39.57
Vehicle Interface	17.16	23.30	20.45	22.63
Experiments	53.76	82.92	20.67	66.85
Propulsion	-	107.12	60.30	-
TOTAL	401.68	501.97	368.72	260.72

Power Subsystem

The power subsystems of the four S/C weighed from 50 to 74 lbs and were different in many respects. A summary of some important power system parameters is given in Table 3.

Table 3
S/C POWER SYSTEM PARAMETERS

	MAGSAT	AMPTE	NOVA 3	Polar BEAR
Orbital Avg Power (W)	120	89	72	31
Total Weight (lbs)	50.32	65.21	73.81	59.28
Bus Voltage (volts)	16.7	28	16	10.7
- # battery cells	12	22 [1]	12	8
- A-Hr rating	8	4	12	12
Array watts/lb	5.76	5.28	2.39	1.25
- watts (min, BOL, at array)	128 [2]	140	100	42
- weight (lbs) [3]	22.2	26.5	41.88	33.52

1. Redundant batteries each with 22 cells.
2. Conservative estimate.
3. Weight includes arrays, drive electronics and shafts, motor inverters, hinges, hinge spacers, and spars.

The MAGSAT power subsystem consisted of four solar panels (14.74), hinges and drive (5.80 lbs), a NiCd battery (11.85), five DC/DC converters and a regulator (12.03), an inverter (1.62), shunt drivers (2.34), a battery current and voltage limiter (0.35), and miscellaneous solar array diodes, fuses, and resistors (1.94).

The AMPTE power system contained four solar panels (21.25), hinges (5.25), redundant NiCd batteries (23.37), redundant main converters (7.96), coulometers (2.42), and charge regulators (2.43), and a power relay control box (2.53).

The NOVA system was comprised of four solar panels (27.02), spars and drive (14.86), a NiCd battery (18.23), three DC/DC Converters (7.34), and a battery charge regulator (6.36).

Finally, the Polar BEAR power system consisted of four solar panels (29.92), hinges (3.60), a NiCd battery (14.44), two converters (9.80), shunt drivers (1.02), and a battery current and voltage limiter (0.50).

The major weight differences in the power system hardware were in the solar panels / hinges / drive combination, the batteries, and the electronics. Solar panel / hinge / drive weights were a function of the orbital average power requirement, the attitude system, construction method, solar cell efficiencies, and whether the panels were rotatable. The weights varied from 22.2 lbs for MAGSAT (sun synchronous, rotatable, honeycomb construction, high efficiency cells) to 41.88 lbs for NOVA (non-synchronous, heavy spars used to reduce shadowing and rotate the panels). A rough calculation of solar panel watts/lb is given in Table 3. The results show the large increase in solar array efficiency due to attitude systems that track the sun line (MAGSAT and AMPTE).

The battery weight difference was due to a larger energy storage requirement (NOVA) and redundancy (AMPTE). A good rule of thumb for battery weight is 0.125 lbs / A-Hr cell. Assuming 1.25 volts / cell, this translates to 10 watt-hours / lb.

The remainder of the power subsystem weight differences were the result of different configurations (# of converters, charge controllers, voltage and current limiters, coulometers, etc.), and redundancy in these units. Weights varied from 11.32 lbs (Polar BEAR) to 18.28 lbs (MAGSAT).

In general, the <u>basic</u> power subsystem of the S/C considered weighed in the 50 to 60 lb range with any features like redundant batteries, exotic spars, A-Hr cell totals > 96, etc. being additional. Lighter solar panels could presumably reduce the weight of Scout class power systems to the low to mid 40 lb range assuming orbital average powers in the 70 - 80 W range and non-sun synchronous orbits.

Telemetry

The MAGSAT TLM subsystem was a partially redundant, fixed format, PCM system that weighed 12.12 lbs. It had three, 64 channel analog subcommutators, two, 16 channel digital subcommutators and a real time data rate of ~ 2 kbps. It received serial, digital data from six different sources and sent the data either to the transmitter or to redundant tape recorders.

The AMPTE TLM subsystem was a partially redundant, microprocessor based system. It had 160 analog, temperature, and differential channels, 128 discrete digitals, 8 serial digital lines, 4 science data interfaces, and a bi-directional data bus to the command subsystem. The system had a 3.3 kbps real time downlink / tape recorder input data rate. The system had several alternate modes of operation and weighed 11.61 lbs.

The NOVA TLM system was a partially redundant, PCM system which has 110 channels of analog, temperature, and differential data and 96 discrete digitals. The system received serial, digital data from five different sources and downlinked the data at a 325.5 bps or a 1.3 kbps rate (memory dump mode). The system had several different TLM modes and modulation control switching states (the latter being the only redundant portion of the system) and weighed 4.73 lbs.

The Polar BEAR TLM system consisted of a non-redundant, 35 channel, analog commutator for housekeeping data and a Science Data Formatter (SDF). The SDF received and formatted digital data from four different sources and sent the data at a four kbps rate to the Beacon experiment for transmission to the ground. The system had 4 different modulation control modes and a power management timer and weighed 4.51 lbs.

Telemetry systems consist of TLM electronics, 4th stage interface (I/F) circuitry, commutators, and data formatters. Weight differences are mainly due to differences in the capability (i.e. # of interfaces, features, etc.) and the amount of redundancy of the subsystem.

Command

The command subsystems consist of Command logic, power switching, and, in the case of NOVA, the Fast Bit Detectors. Command receivers are considered part of the RF subsystem and Command converters are part of the power subsystem.

MAGSAT had a fully redundant, RCA 1802 microprocessor based, command logic subsystem and power switching modules which were redundant to the relay coils, typical of APL built command systems. The system had the capability of ~ 70 relay/pulse commands, variable length delayed commands, a 768 bit long data command, and two, 24 bit short data commands. It weighed 11.92 lbs.

The AMPTE command subsystem also had a fully redundant, RCA 1802 microprocessor based, command logic system. It had the capability of ~ 55 relay/pulse commands, 40 logic commands, and four long data commands. The memory could hold eight delayed command sequences simultaneously. The power switching unit was redundant to the relay coils. Two series regulators in each unit provided the required voltages. The system also provided the separation timing, the low voltage sensing function, and had a bi-directional data bus to the TLM system. It weighed 20.93 lbs.

The NOVA command subsystem was a fully redundant system which could implement 64 relay/pulse commands, and five, 16 bit short data commands. It also had delayed command capability. The system included redundant fast (1 kbps), and slow (10 bps) bit detectors and weighed 9.83 lbs.

The Polar BEAR command system consisted of 16 relay commands which implemented ~ 31 functions by the effective use of switches. The system was non-redundant and weighed 3.40 lbs.

The command system weight differences were due to capability differences (# of relay, pulse, long and short data, and delayed commands) and redundancy.

Data Storage

MAGSAT had redundant tape recorders (35.1 lbs) each of which had a $9x10^7$ bit storage capability. AMPTE carried a single recorder (25.2 lbs) with a $2x10^8$ bit storage capacity. Included in the AMPTE recorder weight was ~ 5 lbs of shielding material.

Based on a sample of two, the tape recorder weights were in the 17 to 20 lb range with deltas due to redundancy, shielding, and to a smaller degree, storage capacity. Different storage technology (e.g. solid state memory) or a larger sample of tape recorder will change these results however.

RF

The RF system consists of oscillators, power amplifiers, command receivers, transceivers, S/C subsystem antennas, multipliers, modulators, filters, diplexers, etc. Experiment antennas are considered part of the experiment system. RF system weights varied from 10 to 20 lbs depending on the downlink frequency, tracking, and link requirements.

Both MAGSAT and AMPTE had redundant S-Band transponders which operated through the GSFC Satellite Tracking and Data Network (STDN). In addition, MAGSAT had a 162/324 MHz Doppler beacon onboard which was required to meet the magnetometer tracking accuracy specification. AMPTE had four, quadrifilar helix, S-Band antennas, two each in the +Z and -Z directions.

Both NOVA III and Polar BEAR were VHF systems operating on 150/400 MHz. The NOVA 150/400 MHz power amplifiers were heavy relative to those of Polar BEAR due to the higher output power requirement ($\geq$ 5.3 dBW vs 1.25 dBW at 400 MHz and $\geq$ 1.8 dBW vs. -3.0 dBW at 150 MHz). In addition, the NOVA 150/400 MHz antenna is a quadrifilar helix while Polar BEAR uses a dipole. Since the Polar BEAR science telemetry is transmitted through the Beacon experiment antenna, 1/2 of the Beacon antenna weight was placed in the RF system.

Thermal

Thermal systems are generally in the 5 to 7 lb range for the basic system including MLI, heaters, coatings, and radiator panels. Louvers, plume protection, and any fine attitude or experiment thermal control are additional. Without the additional items listed, the MAGSAT and AMPTE thermal subsystems would weigh 6.97 and 6.32 lbs respectively. NOVA III and Polar BEAR weigh 5.19 and 6.64 lbs.

Attitude Control and Coarse Determination

The attitude control and determination specifications for the four S/C are given in Table 4. The four attitude systems were very different. MAGSAT had a three axis active system with a reaction wheel and redundant gyros for pitch control, a Z coil for roll/yaw control, and X and Y coils for reaction wheel momentum dumping. Attitude was sensed by a three axis magnetometer, and a digital solar attitude detector and an IR Scanner. The system had a microprocessor based controller and weighed 39.58 lbs.

AMPTE was a spin stabilized S/C which used a three axis coil system and cold gas thrusters for primary and secondary spin axis pointing and rate adjust. The system, which weighed 37.94 lbs, also included a three axis magnetometer and a DSAD for sensing attitude and a nutation damper.

Table 4
ATTITUDE CONTROL AND DETERMINATION SPECIFICATIONS

	MAGSAT	AMPTE	NOVA 3	Polar BEAR
Control	3 axis active < 2° pitch < 3° roll, yaw	Spin stab ± 3°, Z axis	Grav Grad ± 0.5° bias ± 3° oscil. 3 axes	Grav Grad ± 10°, 3 axes
Determination	± 1° coarse 13 arcsec fine 3 axes	± 2°, Z axis	± 1°, 3 axes	± 2°, 3 axes

NOVA was a gravity gradient system with a 26' Astromast boom which used the OATS tank as the end mass. The system included a momentum wheel for yaw control, X and Y coils for S/C spin-up prior to OATS firing, and a Z coil for magnetic capture after reaching its final orbit. A three axis magnetometer and both spinning and non-spinning DSADs were used for attitude determination. To provide yaw control in the event of a momentum wheel failure, two moment of inertia weights were placed on the X axis solar panels. A nutation damper and hysteresis rods were also part of the system. The system weighed 49.62 lbs.

Polar BEAR was also a gravity gradient system which weighed 27.47 lbs. It employed a bi-stem boom with a libration damper as part of the end mass. A momentum wheel provided yaw control. A vector magnetometer and DSADs yielded attitude information and a Z coil was used for magnetic capture. Hysteresis rods were included for damping purposes.

Roughly, the attitude systems in this survey that required ~ ± 2° control weighed in the upper 30 lb range for the basic system. This includes MAGSAT, AMPTE, and NOVA III. (NOVA's MOI weights (9.6 lbs) are considered an add-on to the basic system.) Dropping back to a ± 10° control requirement reduced the system weight to the upper 20 lb range (Polar BEAR). These numbers however, are very rough. A MAGSAT type, three axis, active system which does not require redundant gyros and the aero trim boom would weigh on the order of ~ 31 lbs. The AMPTE cold gas system was used only in the post-launch phase of the mission in order to quickly achieve a favorable power profile. Without this requirement, the AMPTE attitude system would have weighed only 13.5 lbs.

Fine Attitude Control and Determination

This subsystem category was specified in order to more easily compare the coarse attitude and control subsystem weights. Items in this subsystem include star cameras, the attitude transfer system, and the fine sun sensor on MAGSAT and the DISCOS and teflon thruster system on

NOVA. Weights for this subsystem must be determined on a case by case basis.

Harness

Harness weights consist of the S/C harness and terminal boards. Any harness internal to experiments is considered part of the experiment weight. Total harness weight seems to be linearly related to total S/C weight. The numbers vary from 6.4% for NOVA to 7.5% for Polar BEAR (MAGSAT was 6.6% and AMPTE was 7.2%). These percentages are relative to the total weights given in Table 2 (not the actual launch weights).

Structure

The structure subsystem hardware consists of decks, trusses, platforms, columns, bolts, fasteners, brackets, supports, clips, shields, plug covers, battery mounting plates, etc. Structure weights varied from 11.8% (AMPTE) to 16.5% (MAGSAT) of the total S/C weight. The AMPTE ratio was significantly lower than the rest due to the additional weight of the IAR case and fuel (which were considered part of a different subsystem). Adding the IAR case weight to the structure weight brings the percentage up to 14.4%.

The ratio of structure plus propellant case weight (less any items that are not part of the basic structure) to total S/C weight therefore varies from 14.4% to 16.5% for the "basic" structure. The ratios for the four S/C are given in Table 5 below.

Table 5
STRUCTURE PLUS PROPELLANT CASE TO TOTAL S/C WEIGHT RATIOS

	Structure + Prop Case	Total S/C Weight	Ratio
MAGSAT	66.31	401.66	16.5%
AMPTE	72.21	501.95	14.4%
NOVA III	53.38	368.72	14.5%
Polar BEAR	39.57	260.72	15.2%

Vehicle Interface

Vehicle interface subsystem components consist of any interface and separation hardware, despin system, balance weights, interface harness, separation springs, etc. Subsystem weights are very consistent, varying from 17.1 to 23.3 lbs over a nearly 2:1 ratio of total satellite weights.

Propulsion

Propulsion system weight estimates must be done on a case by case basis. Of the four satellites in this survey, only AMPTE and NOVA had propulsion systems. It should be pointed out that the OATS case on NOVA was the gravity gradient boom end mass and was cataloged as part of the coarse attitude control system.

Experiments

The experiment subsystem consists of the experiments themselves, any internal harness, experiment booms, antennas and antenna mechanisms. The experiment subsystem weight is highly variable from mission to mission and there is no useful rule of thumb in this area. The percentage of the total S/C weight that is available for experiments however, is an important parameter and, although not useful in weight prediction, is of interest.

Several iterative attempts to come up with a good comparitive benchmark for an experiment subsystem weight are summarized in Table 6. The benchmarks tried to take into account the additional weight due to "experiment required" S/C hardware. Each successive attempt resulted in more reasonable comparisons (i.e. the percentages began to converge), however, the results tend to reflect program priorities rather than experiment weight to orbit efficiencies.

Table 6
EXPERIMENT PLUS EXPERIMENT REQUIRED S/C SUBSYSTEM WEIGHT TO TOTAL S/C WEIGHT RATIO

	Exp Wt.	Exper Req'd Subsys Wt.	A *	B *	C *
MAGSAT	53.76	103.1	13.4%	39.0%	39.0%
AMPTE	82.92	26.5	16.5%	21.8%	27.7%
NOVA III	20.67	66.2	5.6%	23.6%	30.5%
Polar BEAR	64.90	7.2	25.5%	28.4%	28.4%

* A = Experiment weight / Total S/C weight.
B = Exper subsystem plus exp req'd S/C subsystem weight / Total S/C weight.
C = Exper subsystem plus exp req'd S/C subsystem weight / Total S/C less propulsion subsystem weight.

The experiment required S/C subsystem weights included such items as tape recorders, fine attitude determination systems, Magsat's doppler system, optical bench, and Instrument Module thermal hardware, the Polar BEAR experiment converter, and the additional weight over the average that was required for NOVA's solar panel spars, battery, and power amplifiers. Normal S/C services such as telemetry, command, power (bus voltage only), structure, etc. were not included.

Table 7

SUMMARY OF THE SUBSYSTEM WEIGHT TRENDS / RULES OF THUMB

Subsystem	Trend / Rule of Thumb
Power	Generally 50 to 60 lbs for the basic system with features such as redundant batteries, exotic spars, and A-Hr cell totals > 96 being additional. Weight differences due to different solar panel designs, battery sizes, and electronics configurations. The weight of some systems could drop to the low to mid-40 lb range with new panel designs.
Telemetry	Weight varied from 4.5 to 12.1 lbs. Differences due to the capability (# of analog and digital housekeeping, digital serial, and science channels) and redundancy.
Command	Weight varied from 3.4 to 21.0 lbs. Differences again due to the capability (# of relay, pulse, long and short data, and delayed commands) and redundancy.
Data Storage	Tape recorder weights in the 17 to 20 lb range (sample of 2) with deltas due to redundancy, shielding, and to a smaller degree, storage capacity.
RF	Weight varied from 10.75 to 19.8 lbs. Differences were due to downlink frequency, tracking, and link requirements and attitude stabilization method.
Thermal	Generally in the 5 to 7 lb range for the basic subsystem including MLI, heaters, coatings, and radiator panels. Louvers, plume protection, and any fine attitude or experiment thermal control are additional.
Coarse Att.	Roughly, the three attitude systems in the survey that required ~ ± 2° control weighed in the upper 30 lb range for the basic system while the Polar BEAR ACS with the ± 10° requirement weighed in the upper 20 lb range. Several examples in the text however, violate this trend. Weight should be estimated on a case by case basis using heritage information to obtain piece part estimates.
Fine Attitude	Weight strictly a function of capability, requirement, and redundancy.
Harness	Weight varies from 6.4% to 7.5% of total S/C weight.
Structure	Ratio of structure plus propellant case weight to total S/C weight varies from 14.4% to 16.5% for the basic structure.
Vehicle	Weight varies from 17.1 to 23.3 lbs over a nearly Interface 2:1 ratio of total S/C weights.
Propulsion	Weight estimate must be made on a case by basis.
Experiments	No rule of thumb or trend in this area. Difficult to formulate a reasonable comparative benchmark. Tends to drive S/C subsystem design in that much of the subsystem weight is "experiment required". An attempt at several comparative benchmarks is given in Table 6.

SUMMARY

The paper presents the results of a study which compared the subsystem weights of four Scout class S/C for future weight estimation purposes. The four S/C were MAGSAT, the AMPTE Charge Composition Explorer, Polar BEAR, and NOVA III. The S/C were chosen primarily because detailed weight and capability information was available, their total weight was in the Scout class, and their subsystems were not related by "heritage".

A weight accounting system was developed to normalize and better compare the data. Thirteen subsystems were defined and are listed in Table 1. The components allocated to each subsystem are specified in the individual sections in which the subsystems are discussed.

Table 2 provides a summary of the S/C weight by subsystem. All weight information was taken from the latest weight reports for each of the S/C. Total weights in Table 2 reflect the total weights as given in the weight reports and not necessarily the launch weight of the S/C.

In order to properly compare the S/C subsystems, some information regarding the satellite requirements and the subsystem capability / redundancy was presented. Weight trends were determined where appropriate and are summarized in Table 7. In several cases, the weight trends were developed for the "basic" subsystem weights and "add-on" weights were considered separately. Two of the subsystems which are generally difficult to estimate at the conceptual design level, structure and harness, were consistently a fraction of total system weight, an important piece of information for weight estimation of new designs.

It is important to keep in mind that the trends developed here are for only four S/C which is not a large statistical sample. The addition of a fifth or sixth S/C would probably shift the observed trends somewhat. The results also probably tend to reflect APL design and fabrication methods.

In spite of the small sample, several weight trends were developed which should be useful in estimation of subsystem weights at the conceptual design level.

ACKNOWLEDGEMENT

The author wishes to acknowledge the U.S. Air Force Space Division, Space Test Program under whose sponsorship this work was conducted. In addition, the efforts of J.T.Mueller, D.F.Persons, and many other members of the Applied Physics Laboratory staff who patiently answered many questions regarding the weight and capability of the various subsystems is greatly appreciated.