Power Design Document

Emerald Nanosatellite: Space Systems Development Laboratory

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1. OBJECTIVES

The objective of the Emerald Power System is to provide reliable power for all experiments and satellite subsystems. Emerald will use a basic power system divided into sections: batteries, Power Distribution Unit (PDU), latch-up circuitry, and telemetry (health & status monitoring). This modular system allows a parallel design process and provides a generic power system that can be reused on future missions.

The power subsystem has interfaces to several other subsystems and devices. Each agreement consists of a voltage, current, and a corresponding time. The systems to which power interfaces are Commands and Data Handling (C&DH), Payloads (VLF, Thrusters), Attitude Determination & Control System (ADCS), and Communications (Comm). The power calculations will determine margins and strict guidelines by which power is distributed to each subsystem. A current listing of these calculations can be found in Appendix A.

2. INPUTS/OUTPUTS

The inputs and outputs of the power subsystem are best defined by the schematic drawing of the system. The following chart illustrates the monitors, supplied voltages, required commands, and ground support inputs for this subsystem. The current Emerald design calls for an I^2C interface and a Dallas 1-wire interface. All analog current and voltage signals will be run through an A/D converter and sent via I^2C to the C&DH system. All temperature sensors will be sent via Dallas 1-wire to the C&DH system.

All power switching will be conducted via the Dallas 1-wire system. These inputs will originate at the C&DH system. System power may also be toggled autonomously using the latch-up circuitry. The latch-up circuitry can be manually over-ridden by C&DH toggle commands in case of latch-up failure. Figure 1 illustrates the throughput for the Emerald Power system.

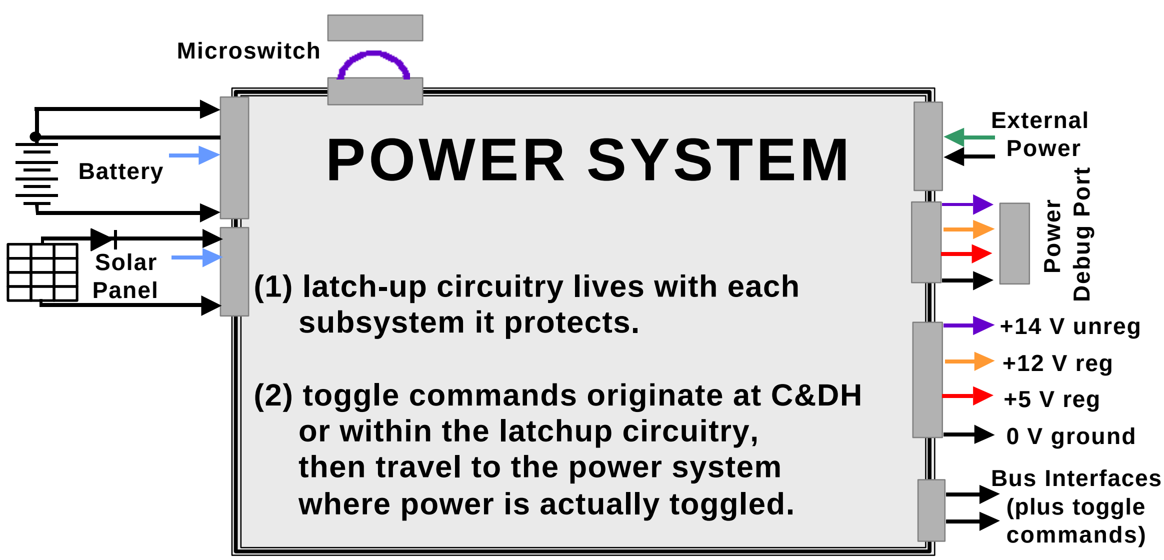

Figure 1: Power System Inputs and Outputs

3. INTERFACES

The power subsystem has interfaces to several other subsystems and devices. Table 1 shows the current interface agreements for the Emerald Power System. This table represents a strict allocation of power resources within the satellite. Each "allocation" consists of a voltage, current, and a corresponding duty cycle. The systems to which power interfaces are Commands and Data Handling (C&DH), Science (all onboard experiments), Attitude Determination and Control System (ADCS), and Communications/GPS.

Table 1: Emerald Power Interface Agreements

	Power Loads (Watts)		
Component	**Stand-by**	**Active**	**Basis of Estimate**
GPS	0	2.7	Prototype
Intersatellite Link	0	3.1	Prototype
Micro Thruster	0	4	Estimate
Radiation Testbed	0	1	Prototype
VLF Receiver	0	0.5	Heritage
CPU	1.5	1.5	Heritage
Communications	1.1	9.1	Estimate
ADCS	0.25	1	Heritage
Telemetry	0.5	0.5	Estimate
Mechanisms	0.5	6	Estimate
Power dissipation	0.75	0.75	Estimate
Distributed Comp.	0.1	0.1	Estimate

4. REQUIREMENTS

The power system must adhere to requirements set by other systems to make the Emerald mission a success. Many of these requirements are governed by the power budget since most requirements placed on power relate directly to the interface that system has with power. In addition to requirements imposed on power, there are many requirements power imposes on other systems. The power budget does not capture these requirements, so they are detailed below.

4.1 Imposed On Power

The Emerald Power System has numerous requirements imposed upon it. The following criteria must also be adhered to:

- Fits inside the specified volume/mass, according to the volume/mass budget
- Survives launch loads, verified through vibration test
- Survives on-orbit thermal environment, verified through thermal-vacuum test
- Survives on-orbit radiation environment, long enough to complete the mission
- Poses no explosive risks
- The satellite will be unpowered during launch, and will turn on after it is released from the launch vehicle
- In itself consumes no more than what is specified in the power budget (under power conversion efficiency)
- Provides regulated voltages to other subsystems on the spacecraft

- Power will be distributed in a "tree" fashion throughout the spacecraft, centered at the power subsystem
- Provides individual power control to the individual subsystem, controlled by the CPU
- Power budget includes a 20% safety margin
- Four independent inhibits to power system for launch

4.2 IMPOSED BY POWER

The power system imposes requirements that must be met to make the system function properly. These requirements are detailed below. The Mission Requirements Document also contains this information to ensure that each subsystem adheres to all requirements imposed upon it.

4.2.1 ATTITUDE DETERMINATION & CONTROL

(a) No preference, but team should be advised of ADCS plans.

4.2.2 COMMAND & DATA HANDLING

(a) High-Level Commands
   - ReadPowerTelemetry – start cycle through all power sensors, packages data for subsequent downlink.

(b) Low-Level Commands
   - PowerTemp – cycle through all temperature sensors in the power system.
   - Power Voltage – cycle through all voltage monitors in the power system.
   - Power Current – cycle through all current monitors in the power system.
   - Toggle_X_ -- TBD toggles for each component requiring switching

(c) 24 telemetry sensors (12 current, 12 voltage), sample rate LOW

(d) 12 temperature sensors (Dallas 1-wire)

(e) Periodic telemetry “dump” for monitoring purposes.

4.2.3 COMMUNICATIONS AND GPS

(a) Downlink capability for telemetry data collection, duty cycle not important as long as it is periodic.

4.2.4 POWER

(a) 0.75 W continuous

4.2.5 STRUCTURE AND MECHANISM

(a) Mass < 2.5 kg

(b) Volume:
   - Battery Box: 16.7 x 3.4 x 5.9 cm^3
   - PDCU Box: 18.7 x 5.4 x 7.9 cm^3

(c) Solar panel area = 53.8 square inches

4.2.6 THERMAL

(a) Battery temperature range TBD

(b) Electronics temperature range TBD

4.2.7 MISSION OPERATIONS

(a) Orbit TBD requirements

(b) Priority given to power system during low-power mode (i.e. Payloads can be run only when there is sufficient power to run them).

(c) Periodic contacts for telemetry data collection

4.2.8 TESTING

(a) Thermal Vacuum Testing TBD days, at TBD levels

(b) Thermal Cycling TBD days, TBD levels
(c) Vibration Testing, TBD levels
(d) Operational Tests—sequence, "fly the spacecraft," etc.
(e) Functional Testing—micro-switches, latch-up, toggles, calibration, etc.

5. DESIGN

The Emerald Power System design relies heavily on heritage from the first two SSDL satellites. On both spacecraft, the power system was reliable, but had room for improvement. For Emerald, the items that could be, or needed to be improved, have been updated to include the new design changes.

Figure 2 shows the Emerald design in a functional block diagram. This system is quite simple, as shown, which increases its probability of reliable success. The following section contains a more detailed discussion of the power system design.

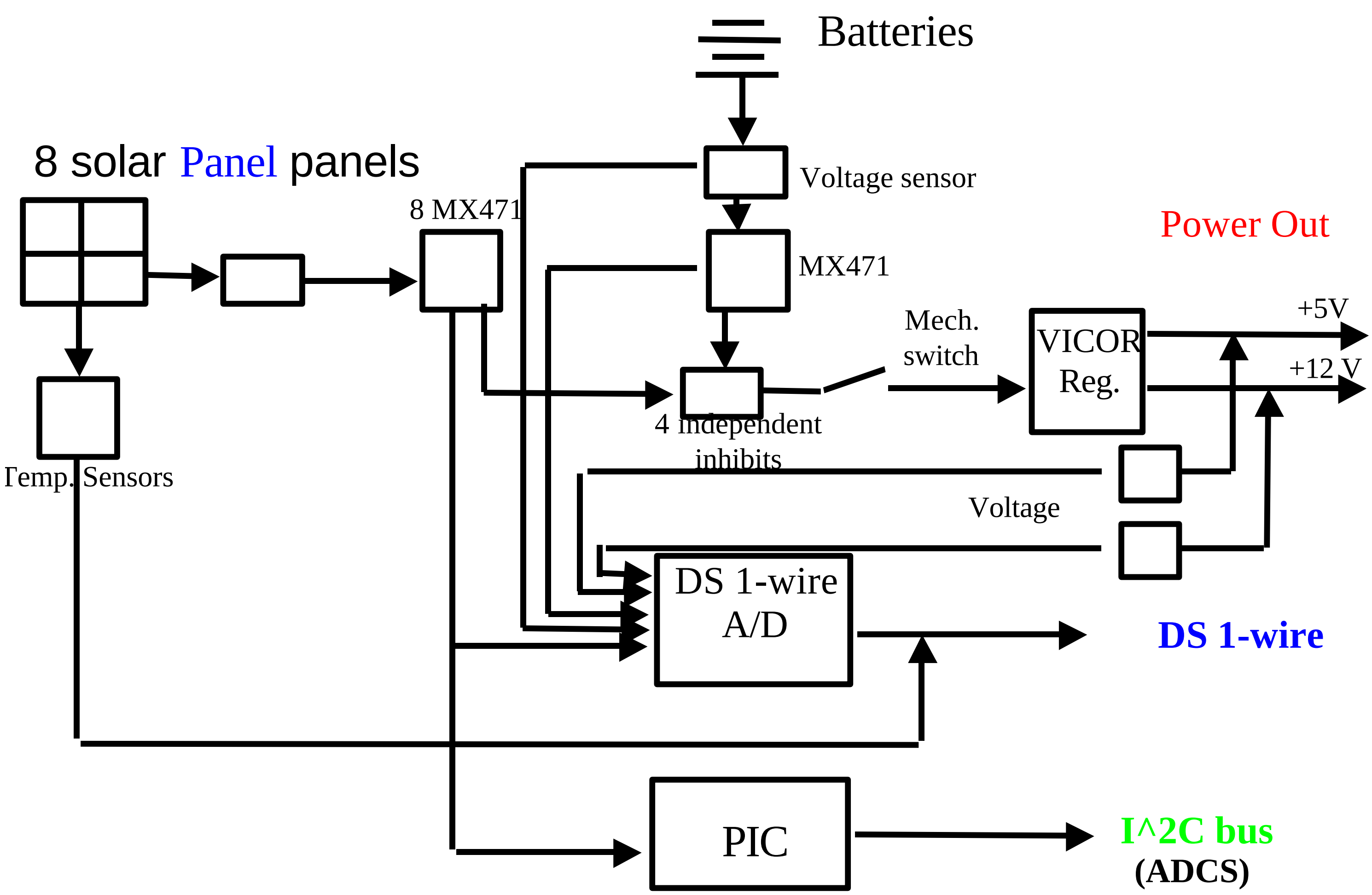

Figure 2: Emerald Power Functional Block Diagram

5.1 FUNCTIONAL DESCRIPTION

Power from the solar cells is sent to the batteries, which have been sized to obviate the need for shunting mechanisms. Power flows from the batteries to the MAX 471 current sensor, which determines how much current is being drawn by the satellite. From there, the power is sent to two Vicor voltage regulators, one producing a 12 V-regulated line and one producing a 5 V-regulated line. These are the two buses for the satellite. The 12 V bus was chosen over an 8 V bus because (a) sufficient voltage in the solar cells (~17 V) was available to make a 12 V bus possible, and (b) a 12 V bus is more standard and thus easier to interface with other COTS hardware (This was the major system trade for the power team—more trades are discussed in section 0). The voltage from the regulators is passed through a voltage regulator to make sure the correct voltage is on the line. The power is sent to the rest of the spacecraft. Both the current and voltage analog data are digitized by a DS2450 A/D converter and made available to the Dallas 1-wire bus. Temperature data is sensed and made available to the Dallas 1-wire bus by a Dallas DS-1820 device. The current telemetry is sent to the PIC that will be added to the PDCU for ADCS.

5.2 POWER GENERATION

Battery capacity requirements have been estimated using a spreadsheet. Below is an explanation of the results of the calculations.

5.2.1 SOLAR CELL STRING GEOMETRY

There will be 8 cells in a string, occupying a total area of 26.9 sq. in. In all calculations, it was assumed that the satellite would be seeing one panel at any one time. We used these calculations to estimate a worse case scenario. Moreover, we assumed time illuminated per orbit to be 78.3 minutes.

5.2.2 OUTPUT POWER AND VOLTAGE

The Spectrolab solar cells that were donated have an efficiency of 24%. Including manufacturing losses and eclipse time, and assuming an orbit period of 94.6 minutes, the output power of the two-string configuration is assumed to be 9.3 W averaged over the course of one full orbit. The expected voltage output of the cells is 17.2 V.

5.3 POWER STORAGE (BATTERY SIZING)

The batteries were sized in two ways: using the C/10 trickle charge method and using the Larson and Wertz, Space Mission Analysis and Design text's method. The former calculations indicated a battery capacity of 1.21 A-h was required, while the latter indicated a battery capacity of 1.70 A-h was required. The power team has procured 2.3 A-h NiCd (mass=0.058 kg, vol=1.27 cu. in.) batteries as well as 2.1 A-h Nickel-Metal-Hydride (NMH) (mass=0.038 kg, vol=0.693 cu. in.) batteries for testing in the power system engineering model. These are both 1.2 V C-size batteries, and will be placed in a stack of ten to produce the 12 V unregulated power that will be sent to the Vicor regulators. Thus the total mass of the NiCd system is about 1 kg, and the total volume is about 335 cu. cm. The total mass of the NMH system is 0.38 kg, and the total volume is 6.93 cu. in. We decided to use the NiCd system because of its heritage. The increased power density of the NMH is advantageous, but both the SSDL and space industry in general have used NiCd much more frequently.

5.4 OPERATIONAL MODES

Though the operations team has not yet enumerated operational modes, "mock" modes were created to determine whether the satellite was generating sufficient power. These modes also allowed an estimation of how long certain experiments could be run before they needed to be shut down to allow the batteries to recharge. Those modes appear in the operations spreadsheet at the Emerald website.

6. SUBSYSTEM COMPONENTS

As discussed above, the Emerald power system is made up of several components. Each major component is listed below. Note that the team has procured at least one sample of each component, many of which will be actual flight hardware.

6.1 SWITCHING/LATCH-UP (MOSFET TRANSISTORS)

- Vishay/Siliconix "LittleFoot"
- Heritage: Pathfinder

6.2 DISTRIBUTION (DC/DC CONVERTERS)

- VICOR VI-J01-CZ (12V) and VI-J00-CZ (5V)
- Temperature: -25 to 85 C
- Heritage: Sapphire, Opal

6.3 HEALTH/STATUS

- Current: Maxim 471
- Temperature: Dallas DS1820
- A/D Converters: Dallas DS 2450

6.4 GENERATION (SOLAR PANELS)

The team is joyful for the donation from Spectrolab, which will provide the solar cells for Emerald.

6.4.1 SPECTROLAB CELLS

- 3x7 cm cells, 8 cells/string
- Two strings per panel
- 24% efficient

6.5 STORAGE (BATTERIES)

- 12Vdc bus voltage
- Passive charge control
- No shunt
- NiCd, 5Ahr in-house

7. TRADES/DESCOPES

Of primary concern early in the design process is selection of equipment that will met the mission requirements with minimum impact on schedule, cost, risk, and labor. The Emerald power team was faced with several fundamental trade studies to select between various technologies. Each of the major trades is summarized below.

7.1 BUS VOLTAGE: 12VDC VS 8VDC

- Heritage--Sapphire & Opal both used 12V
- Compatibility--12V bus is more common
- Solar Panel Impact--Panel/cell size (voltage vs. temperature)
- **DECISION:** 12Vdc

7.2 SOLAR CELL SIZE/TYPE: 3X7 CM VS. 2X4 CM

- 3x7 more efficient (24% vs. 17%)
- 3x7 fits better on side panel--fewer strings required
- **DECISION:** 3x7 cm cells, given Spectrolab donation

7.3 SWITCHING: ELECTROMECHANICAL VS. SOLID STATE SWITCHES

- Reliability (probability of failure, vibration, etc.)
- Mars Pathfinder used solid-state devices (Little Foot MOSFET)
- **DECISION:** Solid State Switches

7.4 BATTERY CELL SIZE/TYPE: NMH, NICD, CAPACITY

- Maximize energy density
- Minimize volume/mass
- Sized based on power budget
- **DECISION:** NiCd

8. TESTING & VERIFICATION

During the prototyping stage, converters undergo minimal thermal modeling. This test determines requirements for heat sinking. A junction temperature analysis is employed to ensure safe use of the converters. The power budget is configured such that the converters will not be run at full capacity. This, along with the testing procedures, will help ensure reliability in power distribution.

Before the power system can be integrated with the other systems, it is necessary to calibrate it. The losses due to temperature, electronics, etc. will be computed to determine system efficiency and soundness of design. Power converters are subjected to rated loads during the stress testing. This individual testing is done with external power until steady state. The system is then combined and subjected to similar stress testing via external power. Once a steady state is achieved, there is a "worst case total draw" using external power to test the system.

The batteries will go through a characterization test to determine the state of charge. Matched cells will be purchased if available, but individual cells will be acceptable as long as the following procedure is followed. Each cell will be cycled once before integration into the full stack. While the cells are not matched, each cell's charging curve will be evaluated when the stack is made. The battery stacks will only be charged under supervision to prevent damage. A log will be kept to determine when the batteries must be reconditioned. For conditioning, the rate of charge must be as low as possible at transfer points (preferably C/10). Performance of the batteries is tested when the system is tested on internal power.

Each power converter is tested individually with the battery stack. Stress tests on each part are conducted to steady state, when the system is combined for total system stress testing. Upon steady state, the system undergoes a "worst case total draw" using internal power. The difference between external power (electronic) and internal power (chemical) tests the responses of relays in the power system. Final steady state is achieved, and finally, the batteries are tested for drainage.

With testing completed, the system is delivered for integration. After integration, proper functionality of the power system will be demonstrated during bench-top testing of the spacecraft. To ensure proper system reliability, a thermal vacuum test will be run with the power system in operation. System-level testing will be conducted with the power system integrated to ensure mission success on-orbit.

9. BUDGET

The Emerald power system has a budget of $2000.00 that must be sufficient for two engineering models, and two flight models. The team does not anticipate any problems with this budget, so long as donations are procured when necessary (solar panels, labor for fabrication, etc). Many items shown in the budget below are "TBD." At this stage of design, it is important to note that these items will be purchased. The nest revision of this document will contain more detail as to the budgetary allocation. Thus far, Thang and I have spent over 100hrs on the project.

Table 2: Emerald Power System Budget

Quantity	Component	Notes	Cost	Vendor
4	Battery Stacks	NiCd Cell type	~ $500.00	TBD
8	DC/DC Converter	VI-J01-CZ (12V) VI-J00-CZ (5V)	2-InHouse 6- $600.00	VICOR (OPAL Heritage)
40	Current Sensors	471	Donated	Maxim
44	Temperature Sensors	DS1820	TBD	Dallas
~24	A/D Converters	DS2450	TBD	Dallas
TBD	MOSFETs	"Little Foot"	Donated	Vishay/Siliconix
~512	Solar Cells	3x7 cm cells, 8 cells/string	Donated	Spectrolab, Inc.
--	Solar Panel Fabrication		TBD	
4	PCBs		TBD	
--	Misc. Electronics (resistors, etc)	PDU Flight Hardware and repairs	$71.00	Various
TBD	Latch-up Circuitry		TBD	Various
TOTAL:	**$**	**Anticipated: $2000.00**		**Margin: $0.00**

10. SCHEDULE

The Emerald mission embodies the "better, faster, cheaper' philosophy. With that in mind, the power system will be on an accelerated schedule. Figure 3 highlights important milestones in the power system development. The primary goal is to complete the flight power system by the end of Spring 2000. This is an ambitious, yet feasible goal.

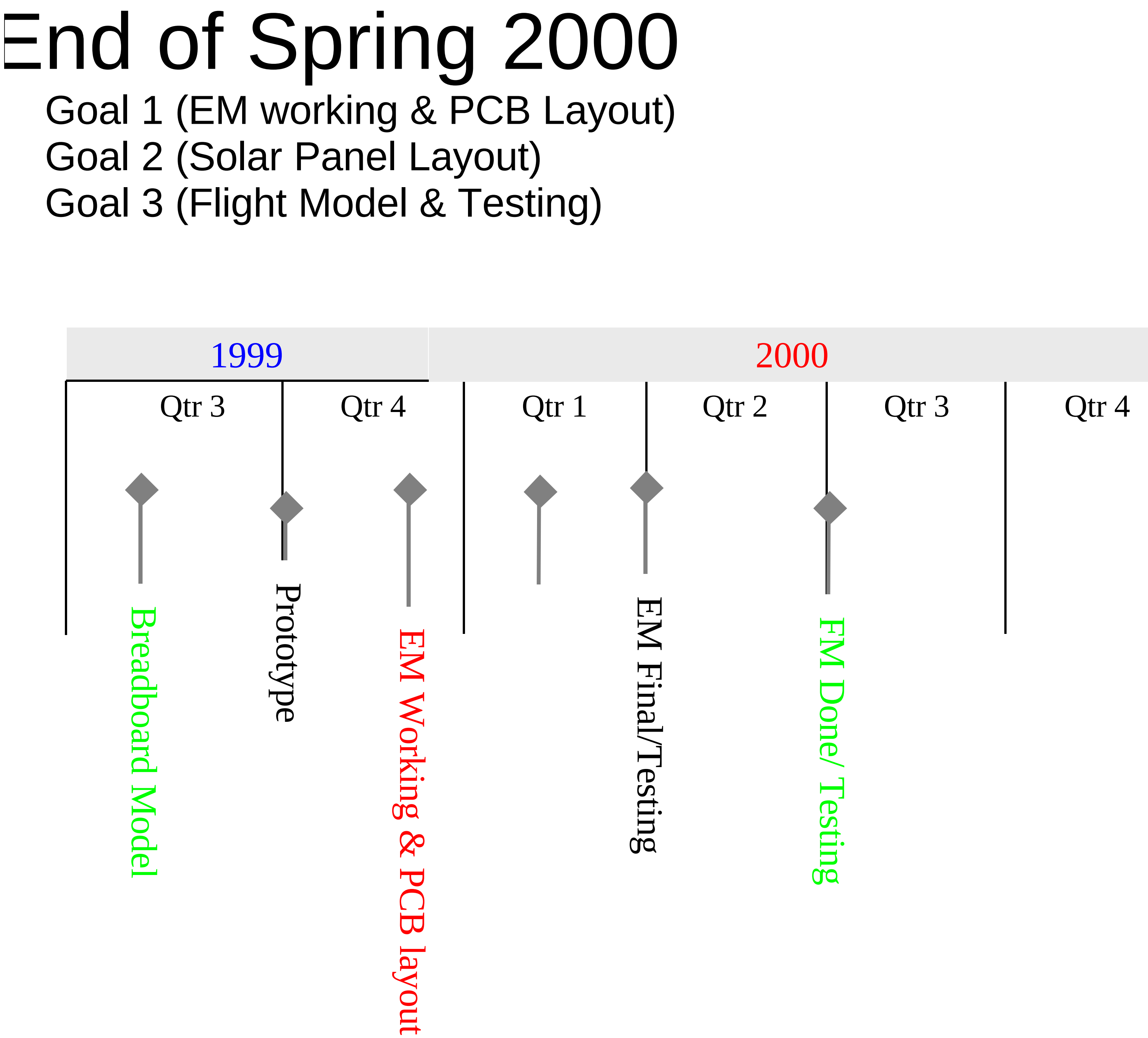

Figure 3: Emerald Power System Schedule

APPENDIX A:

Emerald Power Calculations

Battery System

Cells	Value	Units
Cell voltage	1.2	volts
Cell capacity	5	AH
# of cells/pack	10	cell
# of packs	1	pack
Pack voltage	12	volts
Total capacity	5	AH
Pack energy storage	60	WH
Total energy storage	60	WH

Solar Charging

	Value	Units
Cell size	3.36	sq. in.
Cell current	264	mA
Cell voltage	2.2	volts
S. Area to light	53.8	sq. in.
Time illuminated/orbit	78.3	min.
Cell Power Output	580.8	mW
Cell Pow.Out./S. Area	172.857	mW/sq.in.
Array Power Output	9299.714	mW
Array energy out/orbit	12.136	WH