BROWN UNIVERSITY

Communications

Design and Documentation

EQUiSat

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Complete documentation of the design of the communications subsystem of EQUiSat. Report includes design methodology, descriptions of analysis and results, and parts specifications.

Contents

Introduction

Overview of Mission Goals

A fundamental tenant of the mission statement for EQUiSat is that the satellite be accessible to the general public and be trackable by amateur radio. Thus, the communications link must possess the qualities of a beacon, radiating with sufficient power to reach earth and a frequency appropriate for amateur radio technology. The beacon must be reliable and transmit with consistency. Without a functional beacon, the satellite will be unable to confirm its successful operation.

Moreover, in keeping with the overall mission spirit, the communications system should be simple and low-cost, for ease of reproduction. Additionally, power demands should be minimized to meet the capabilities of a CubeSat whose primary payload is a high-power flash bulb. Both size and mass must be small to meet CubeSat limitations of a 10 cm-sided cube with a maximum mass of 1.3 kg.

Requirements

Link Type

The communications system must necessarily include a down link. To function as a beacon, the satellite should transmit a signal which continuously communicates its presence in a given region.

Frequency

The carrier frequency should be commonly used in the amateur radio world. Moreover, it should encompass communications devices which are available to amateurs at relatively low cost. Finally, the frequency should be as efficient as possible for use in satellite communications to meet the goal of minimizing power demands.

Transmission

The transmission system for the satellite must be reliable and continuous. The communications link is a critical requirement of the satellite and should be as low-risk as possible. It should function given any orientation of the satellite and should transmit with a safe margin for amateur radio reception. The transmitted signal should allow for identification of EQUiSat.

Power

The communications systems must be limited to less than 10% of the satellite's total power demands.

Mass and Volume

Communications should comprise less than 10% of the satellite's volume and mass. Any transmitting antenna must meet the basic requirements of the CubeSat module. Most importantly, it must be contained within the space of the cube during launch, and must not exceed 6.5 mm of clearance from the face of the satellite.

Design Process

Link Type

Three types of links were considered in the design of the communications system. Each was weighed according to its strengths and weaknesses with regards to the mission goals and design requirements. In the end, a one-way, downlink only transmitter was chosen.

Downlink Only, No Telemetry

A downlink only requires solely a transmitting device on a single frequency band, eliminating the need for a receiver device on the satellite. It is therefore the simplest, cheapest, lowest power and smallest option. Moreover, there is no need for a complex ground station with transceiver capabilities. This link-type meets the basic design requirements for a functional beacon and is in keeping with mission goals.

One drawback of this option is its low functionality. It does not perform any telemetry and thus acts as a very rudimentary beacon. A second drawback is that it violates the CubeSat and IARU requirements of an uplink for shutdown of communications. This latter drawback is mitigated by the fact that the transmission will be relatively low-power and by the short lifetime of the satellite, both points which increases the likelihood that EQUiSat may receive a waiver for operation.

Note: If the satellite does not qualify for a waiver of the communications requirements, it may be fitted with an emergency-shutdown uplink. Space, weight and budget will be reserved for this contingency.

Two-Way Device, No Telemetry

This device would have the main advantage of meeting the requirements of CubeSat as well as the IARU, as it would include a shut-down option. The two way device might also allow for some control over the in-orbit spacecraft.

However, two-way communication significantly increases the complexity of the satellite, violating a mission tenant. Moreover, it adds weight and power demands to spacecraft, and requires a much more complex and costly ground station. Finally, control of the satellite will likely be superfluous, as the simplistic spacecraft will not likely have the equipment to benefit from ground-station control.

Telemetric Device

A telemetric device would yield the highest utility of the communications system. It would allow the satellite to transmit scientific data or its coordinate location, greatly facilitating the identification of the satellite.

This option also violates many of the design requirements, however. It is a much higher power device, due mostly to the higher data rate of the transmission. It is also a more complex device with a greater likelihood of failure. The general public would unlikely have the equipment of the satellite's telemetric capabilities. In sum, this option is not relevant to mission goals.

Carrier Frequency

The selection of a carrier frequency band followed the design choice of a one-way device with no telemetry. The UHF band was ultimately selected. Main considerations were the practicality of each frequency band, and maximizing efficiency and accessibility.

Ultra High Frequency Band

The UHF band experiences the least atmospheric attenuation while still exceeding the 100 MHz frequency necessary to penetrate the ionosphere. It is also contains the frequencies reserved by IARU as the primary world-wide AmSat band. This band is furthermore compatible with most handheld Ham radios available on the market.

One disadvantage of the UHF band is that it does not allow for a high data rate. However, given the low data rate of a non-telemetric, one-way device, this factor was determined to be null.

Another disadvantage of the UHF band versus a higher frequency band is the increased antenna size. In general, antenna size increases with wavelength. An antenna radiating at this frequency would have to be collapsed during launch then deployed in orbit, increasing complexity and likelihood of failure. In essence, the trade-off between UHF band and a higher frequency band is the lower power demand versus the risk of a deployment mechanism. Given the very high power demands of the primary payload flashbulb, power minimization was chosen to be paramount for the communications system. This choice was made knowing that antenna deployment mechanisms have flown on most CubeSat without failure, implying only moderate increase in risk.

Very High Frequency Band

The VHF band has only the advantage of low atmospheric attenuation and is limited by a minimum of 100 MHz frequency needed to penetrate the ionosphere. Disadvantages are a low data rate and increased antenna size.

Super High Frequency Band

The primary advantage of the SHF band is the decreased antenna size, as discussed in the UHF band section. Another advantage of the SHF band is its high data rate. However, the low demands of a one-way, non-telemetric device render such a high data rate superfluous.

Disadvantage are the decreased efficiency, the more limited availability of compatible and inexpensive components, and the increased difficulty of receiving approval to transmit in a more coveted satellite band.

Antenna Type

Three basic antenna types were considered: monopole, dipole, and patch. A dipole antenna design was chosen, based in most part on a recommendation by consulting radio expert Ray Zenick. This design decision is justified in the following sections.

Overview

Antenna and radio design is a very complex field, whose subtleties escape this satellite designer. For that reason, only basic antenna types and configurations were considered. This design premise is also in keeping with the mission goals of a simple, readable and reproducible design.

The following is a brief overview of the basics of antenna design with respect to satellites.

Radiation Pattern: Each different antenna design has a different radiation pattern. Only omnidirectional antennas were considered for EQUisSat because the spacecraft will not be able to perform any pointing control, so radio transmission must be received on earth given any satellite orientation. The fact that an omnidirectional, low-gain transmission requires more power than a high-gain, focused transmission was considered. However, the implementation of an attitude control system was determined to be too costly and complex to be worth the improved power consumption rate. EQUiSat is simply too limited a spacecraft to make good use of any attitude and guidance control system.

Size: As a rule of thumb, for any antenna design to be functional it must have a characteristic length of at least ¼ of the transmitting wavelength. For the UHF band, this corresponds to approximately 20 cm of length. The importance of this dimension comes into play in the design of an antenna deployment mechanism.

Placement: The antenna must be placed in such a way that its radiation towards earth is not blocked by the satellite. This is a complex issue that is beyond the scope of knowledge of the designer. Therefore, all antennas were considered to be pointing radially away from the spacecraft.

Dipole Antenna

The dipole antenna is a simple design with easy deployment. It has the advantages of some (low) gain and good efficiency. Due to its two poles, it can be placed in such a way that the satellite body will never block it.

Monopole antenna

Advantages of a monopole antenna are its simplicity and ease of deployment. Disadvantages are the fact that it has no gain, and that it is difficult to place on the satellite in such a way that is never blocked by the satellite body given bad orientation.

Patch Antenna

The main advantage of patch antenna is that it would not have to be deployed, but would rather lay flush against the face of the satellite, eliminating the risk of a deployment mechanism.

However, patch antennas do not function effectively at side length less than ¼ wavelength, i.e. approx, 20 cm, which is bigger than one side of the satellite. For this design to work, the transmission frequency would have to be increased to the SHF range. Even if this were to be done, the patch antenna would still have the disadvantage of occupying valuable satellite surface space needed for solar power generation. Furthermore, the patch antenna is a much more complex design that would require costly custom manufacturing.

Antenna Deployment

The antenna deployment system was designed assuming a dipole antenna. Ultimately, the deployment system chosen for use was tying down the antenna with nylon, then melting the nylon with a nichrome wire heated by passing current through it after launch. The antenna is fabricated from a highly elastic material that springs to a rectilinear shape when released.

Nichrome Melting Nylon

This deployment method has the two main advantages of being completely inert when unpowered and of demonstrated effectiveness. This method has been used on several CubeSats successfully. Moreover, it is a relatively brute deployment method that has only a few modes of failure. The method can be tested extensively on earth before launch.

The greatest risk associated with this deployment method is that the nichrome wire overdraws the batteries when heated, as it is dissipating a significant amount of heat. A timer and low-voltage shutdown circuit should safeguard against such a scenario.

Polyethylene Glue Ablation

This deployment method is created by gluing down the highly elastic dipole antenna with a small dot of polyethylene (i.e. glue gun). The polyethylene will outgas in the vacuum of space, thus releasing and deploying the antenna.

While this is an attractive deployment solution due to its simplicity and passiveness, it violates CubeSat restrictions on high-outgassing materials.

Smart Wire

This third deployment method is the construction of the antenna with a wire such as nitinol, which returns to a "remembered" state when heated. Using nitinol the antenna could be heated and thus deployed simply by passing a current through it.

While this appears to be an elegant solution it is not feasible. In order for a wire to heat up its circuit must have a high impedance, which sacrifices its radiative component. That is to say, an antenna which is an efficient transmitter is not an efficient heating element.

Communications Link Analysis

Design Variables

Transmitter Output: the effective isotropic radiated power from the radio antenna. It is specified by the radio manufacturer to be 20 dBm.

$$T = 20\ dBm$$

Antenna Gain: the gain or "focusing" of the signal by the antenna. For a dipole antenna the value of the gain is 1.7 dBi.

$$G = 1.7\ dBi$$

Receiver Sensitivity: the receiver sensitivity refers to the signal to noise ratio that a receiver is able to detect. Typical receiver sensitivity for a commercial Ham radio is 1.8 uV or -120 dBm.

$$R = -120\ dBm$$

Frequency: the carrier frequency of the radio is 436 MHz, corresponding to a wavelength of 68.8 cm.

$$f = 436\ MHz.\ \lambda = 68.8\ cm.$$

Orbital Altitude: the absolute distance between the satellite and the surface of the earth is assumed to be 300 km.

$$h = 300\ km$$

Slant Range(H): the distance between the satellite and a given point of observation on earth. It depends on the altitude of the satellite and the angle of the satellite from the horizon (θ). Slant range is greatest at angle of 0, when the satellite is first visible and the horizon, and is smallest when the angle is 90 degrees and the satellite is directly overhead. Note that the radius of the earth (r_e) is 6367.5 km.

$$\alpha = \frac{\pi}{2} - \theta - \arcsin\left(r_e * \frac{sin\left(\frac{\pi}{2} + \theta\right)}{h + r_e} \right)$$

$$H = \sqrt{(r_e^2 + (r_e + h)^2 - 2 * r_e * (r_e + h) * \cos{(\alpha)})}$$

Atmospheric Path Loss: The attenuation experienced by radio signal as it travel between the spacecraft and the earth's surface. It is dependent on signal frequency and slant range.

$$L = 20 * \log{(4\pi * \frac{H}{f})}$$

Total Link Margin: the difference between the receiver sensitivity and the sum of the transmitter output, antenna gain, and path loss.

$$Link\ Margin = T + G - L - R$$

Results

Figure 1: Link Margin vs. Viewing Angle is a graph of the link margin as a function of satellite angle above the horizon. The link margin is greater than zero, and thus the satellite signal receivable, for all angles greater than 19 degrees above the horizon.

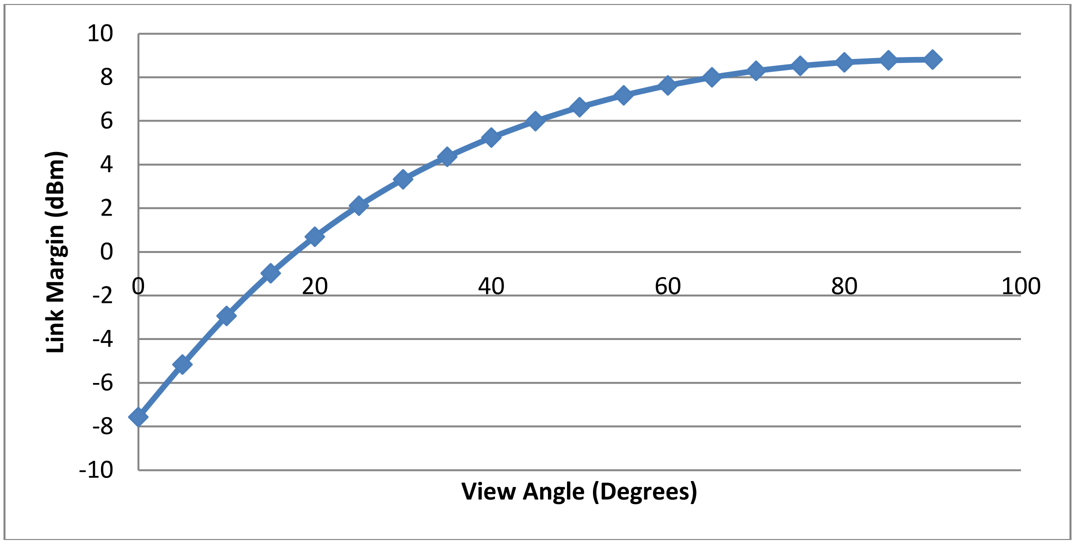

Figure 1: Link Margin vs. Viewing Angle

Component Details

Radio

The selected radio, shown in Figure 2: BeeLine Transmitter Radio, is a simple morse-code type transmitter. It transmits a repeated beeping tone at the carrier frequency by keying on and off. Figure 3: Oscilloscope Screenshot is a screenshot of the transmission recorded by an oscilloscope.

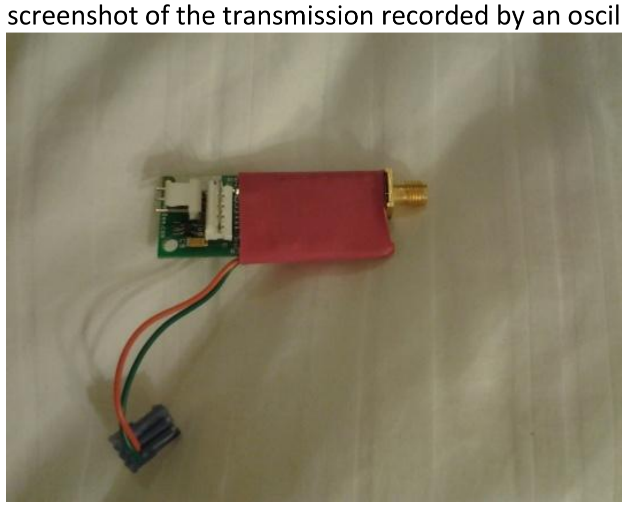

Figure 2: BeeLine Transmitter Radio

Figure 3: Oscilloscope Screenshot

Device Specifications

For complete information see Appendix A: Radio Data Sheet.

<u>BigRedBee 100mW BeeLine Transmitter</u>

- Size: 61mmx22mmx10mm
- Mass: 30 g
- Voltage In: 3.2 to 6.6 V accepted
- Operating Temperature Range: -40 C to +85 C

Configuration Specifications

Mode: FM mode selected due to more common use in amateur radio.

Frequency: The frequency of the radio is selectable between 420 and 450 MHz. The frequency chosen and programmed into the radio is 436 MHz. This frequency falls in the 70 cm, Amateur Radio Satellite Service Primary World Wide, Non-interference Basis frequency band of 435-438 MHz. Further information regarding licensing for satellite transmissions can be found in Appendix B: Satellite Radio Communications IARU Licensing Information.

Power

Table 1: BeeLine Transmitter Experimental Performance Data displays the results of experimental measurements of the radio's performance. Experimental data is subsequently used to calculate the total rate of power consumption by the radio given the chosen duty cycle. The duty cycle of the radio refers to the amount of time the signal is "beeping" on. The radio is configured to beep "on" for 2 seconds, then "off" for 1 second. As shown in the table, the rate of power consumption by the radio is .5 Watts.

Table 1: BeeLine Transmitter Experimental Performance Data

		Transmit On	Transmit Off
Voltage Battery	V	4.07	4.07
Current In	A	0.14	0.088
Power In	W	0.5698	0.35816
Time Cycle	S	3	3

Duty Time	S	2	1
Duty Cycle	x100%	0.6666 667	0.33333 333
Power Cycle	W	0.3798 667	0.11938 667
Total Power	W	0.4992 533	

Legacy

Performance of the chosen radio is qualified by two previous satellite projects. According to the radio manufacturer, the 100 mW Beeline Transmitter was used as a beacon by ITUpSAT1, launched September 2009. SwissCube uses a similar beacon with a radiated power of 120 mW, a comparable power output.

Suggestions for Future

A Ham radio receiver should be procured, and the radio transmission reception tested over long distances, such as in an open field. Orbital distances may be simulated by reducing the power of transmitter. This testing should be done using a commercial antenna to isolate evaluation of the transmitter itself.

Antenna

Specifications

- Dipole length is 17.5 cm each pole, 35 cm total length
- Gain is 1.7 dBi
- Antenna impedance is 75 ohms. Radio impedance is 50 ohms. This leads to a VSWR of 1.5.

Materials

- **Poles**. Constructed from .027” diameter nitinol.
- **Coax Cable**. RG-174U coax cable with SMA connector.

Construction

The following schematic (Figure 4: Dipole Antenna Schematic) shows the basic design of a simple dipole antenna. The antenna prototype constructed, pictured in Figure 5: Photograph of Constructed Dipole Antenna, deviates from the schematic only in that the antenna poles are connected directly to the coax cable components, instead of being wired through a terminal block.

To connect the nitinol poles to the coax cable, they must be spot welded together. Due to high nickel content, the nitinol will not bond to either resin core solder or silver solder. After welding, the coax-to-pole junction is triple wrapped with heat-shrink tubing.

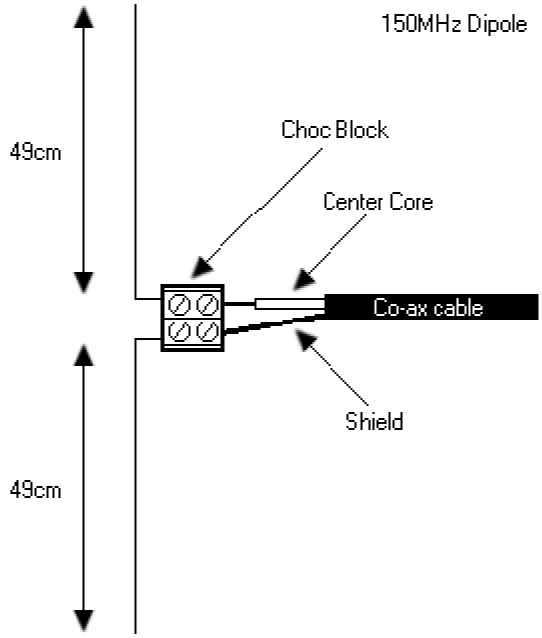

Figure 4: Dipole Antenna Schematic

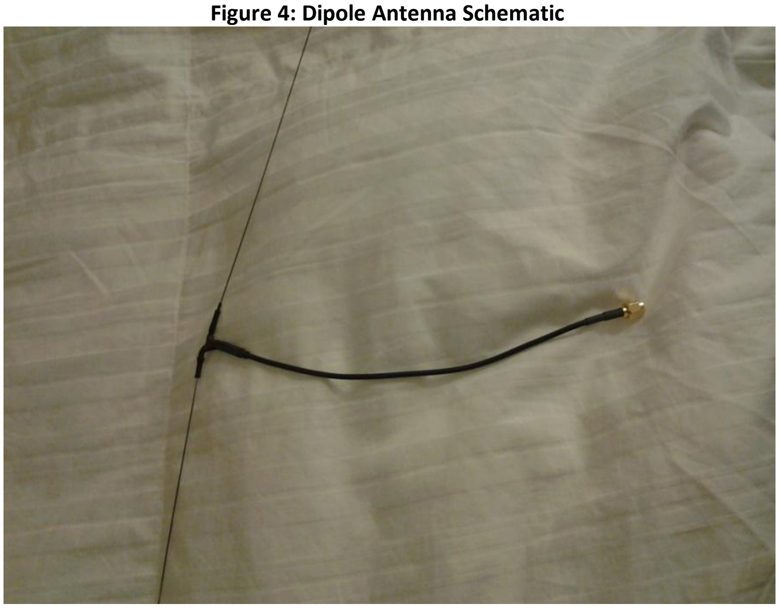

Figure 5: Photograph of Constructed Dipole Antenna

Spacecraft Placement

The antenna is intended to be positioned at corner of cube face with poles pointing radially outward at an angle of 45 degrees from the side of the face, as shown in Figure 6: 45 Degree Dipole Placement, below.

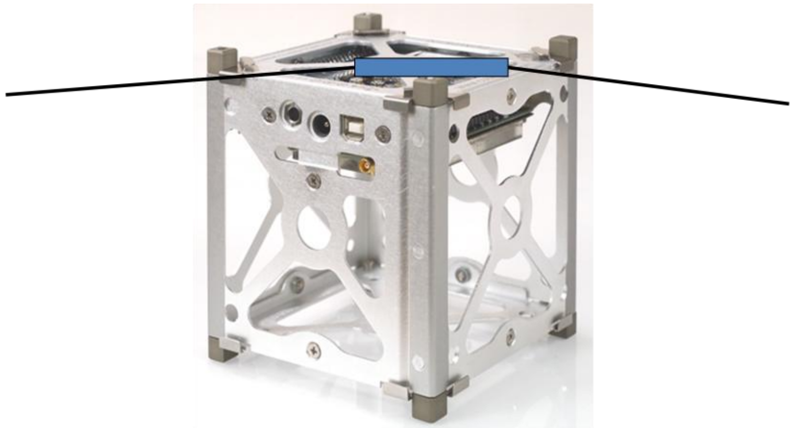

Figure 6: 45 Degree Dipole Placement

Suggestions for Future

After functionality of the radio transmitter is confirmed, it should be connected to the in-house antenna and tested again.

Antenna effectiveness should be evaluated with the satellite at a variety of orientations.

Deployment System

The deployment system functions by tying down the highly elastic nitinol antennae using nylon, or fishing line. Nylon is then melted using a heating element, releasing the antenna.

Heating Element

The heating element used in the deployment system prototype is a nichrome wire used as a foam cutter replacement wire. Basic tests demonstrated that when attached to a 5 V source (equivalent to the main satellite battery supply) the nichrome wire melts through nylon in approx. 3 seconds.

More information on the properties of nichrome can be found in

Appendix C: Properties of Nichrome.

Preliminary Testing

To date, the antenna deployment system has been tested using a wooden block mock-up of the satellite size and geometry to wrap the antenna around, as seen in Figure 7: Deployment Mechanism Testing Apparatus. CubeSat allows 6.5 mm of clearance for protrusion from the face of the cube. The antenna was tied down with nylon, and the nylon melted with nichrome across the terminals of the lithium ion batteries intended for use on the satellite.

These first tests determined that the antenna should be coiled on a single face of the satellite, as opposed to being wrapped around the satellite. It also showed that the chosen deployment system is viable.

Figure 7: Deployment Mechanism Testing Apparatus

Suggestions for Future

It may be beneficial to wire the nichrome wire across battery terminal in series with a resistor, in order to control heating rate. This concept should be varied and tested.

An electrical method of protecting batteries from overdrawing by the nichrome wire must be devised. One possibility is a timer connected to a switch.

Deployment system should be tested under various temperature conditions.

Appendices

Appendix A: Radio Data Sheet

See, http://www.bigredbee.com/docs/beeline/BeeLineDoc.pdf

Appendix B: Satellite Radio Communications IARU Licensing Information

See, http://www.iaru.org/satellite/IARUSATSPEC_REV15.6.pdf

Appendix C: Properties of Nichrome

- Typically, 80% nickel / 20% chromium
- Features: oxidation-resistant, high melting point (1004 C)

Material property	**Value**	**Units**
Modulus of elasticity*	220	GPa
Specific gravity	8.4	Dimensionless
Density	8400	kg/m^3
Melting point	1400	°C
Electrical resistivity at room temperature	1.0×10^{-6} to 1.5×10^{-6}	Ωm
Specific heat	450	$Jkg^{-1}°C^{-1}$
Thermal conductivity	11.3	$Wm^{-1}°C^{-1}$
Thermal expansion	14×10^{-6}	$°C^{-1}$
Standard ambient temperature and pressure used unless otherwise noted.