A CubeSat Radio Beacon Experiment

CUBEACON – A Beacon Test of Designs for the Future

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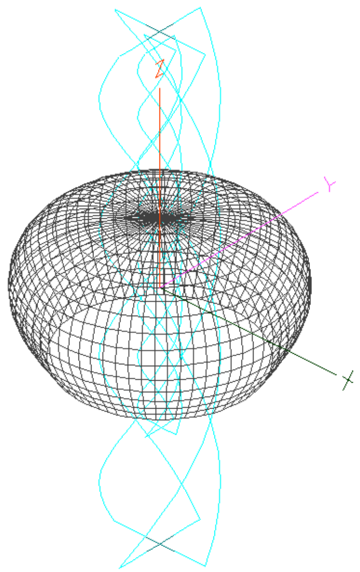
Antenna ?



Multifrequency ?

Size, Weight and Power ?

Phase Coherent ?

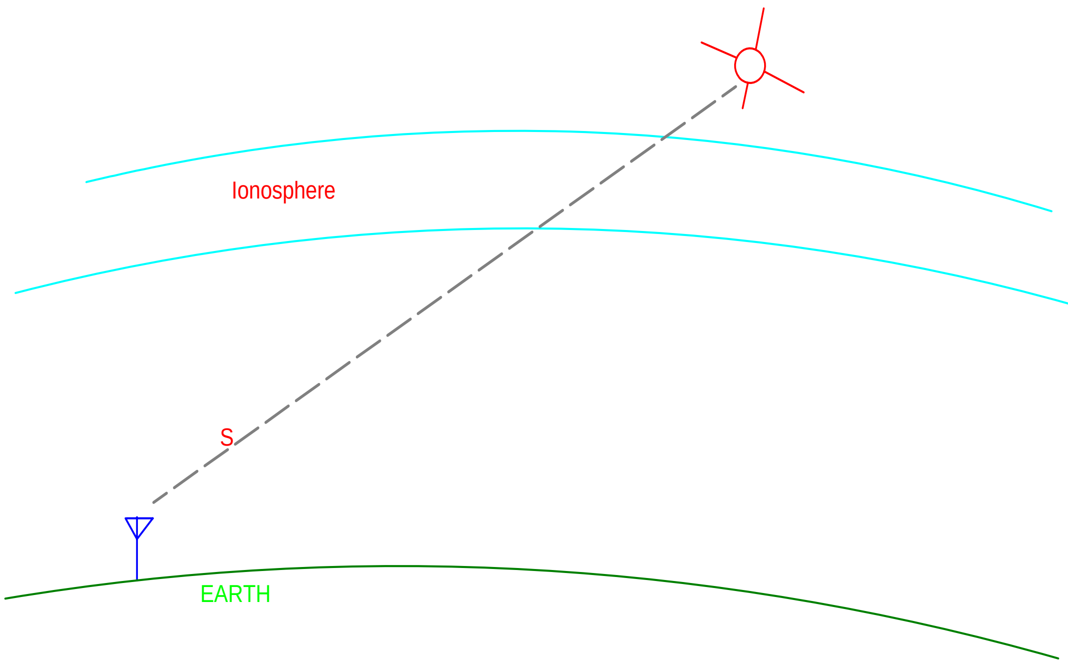
CubeSat Developers Workshop, April 23 2010

San Luis Obispo, CA

CUBEACON – Instrument or Experiment ?

- The beacon apparatus considered here is intended as experiment
  - It tests parts, circuits and mechanisms, some not utilized together before in space
  - Successful operation will provide flight heritage for the designs and materials
  - A prime mission objective of CubeSat development is served
- It is a step in product development
- Similar beacon designs with enhanced material screening will thus be ready to meet the needs for operational instruments in the future.
- Meanwhile use of the CUBEACON can provide useful ionospheric data

CUBEACON – A Beacon System



- A source of radio signals in or above the ionosphere

•Oscillator(s) + Antenna(s)=

Transmitter

- A corresponding receiving set on the Earth

•Antenna(s) + Detector(s) = Receivers

CUBEACON – Beacons of the Past

- Here are examples of some past Radio Beacon experiments, various frequency plans
- GEO spacecraft, using Faraday rotation on 137 MHz linear polarization telemetry

    ATS-1, ATS-3, SanMarco, ETS-2

    And phase coherent signals on

    - ATS-6: 40-140-360, giving phase delay and group delay measurements

- LEO spacecraft, mostly circular polarization
    - TRANSIT: Navy Navigation Satellites: 150-400, modulated navigation message
    - WIDEBAND, 137-413(7)-1239-2891 (3/3/3/7)
    - HILAT, POLAR BEAR, 137-413(3)-1239 (3/3/3)
    - COSMOS various: 150-400 (8/3)
    - CERTO: 150-400-1067 (8/3)
    - DORIS: 401-2036 (5)

POLAR BEAR Spare Apparatus

CUBEACON – More beacon system background

- System for sensing ionospheric characteristics, total electron content (TEC) and variations (scintillations)
- Uses a radio transmitter (modulation optional) on spacecraft with known power and antenna pattern – orbit may be LEO, HEO or GEO
- Receive signals on earth (or vice versa), measure amplitude, phase, polarization
- TEC determined in several ways
  - Faraday rotation of linearly polarized signal, stabilized s/c (VHF) – magnetic field dependence
  - Phase comparison of multifrequency coherent signals
- Transionospheric signals at VHF are strongly affected by irregularities,
  UHF less so, L-band even less , S-band only a little.
  Equatorial & Auroral zone show greatest effects / Seasonal and solar effects = SPACE WEATHER
- Perturbations/ Scintillations long known & measured using beacons as channel probes
  - Scintillation indices may be computed for phase and amplitude variations
- TEC measures and Scintillation Indices feed operational near real time ionospheric models along with other data to predict propagation conditions
- GPS signals can produce similar measurements from a different perspective with less sensitivity
- Considered here is a LEO based transmitter of a multifrequency coherent beacon system

CUBEACON – How Does this Beacon System Work

- Phase path $\Phi = S - \int \varepsilon N \, dS/cf^2$ radians
  where N = electron density electrons/m^3, f = frequency Hz,
  S = physical path m, $\varepsilon = 8.854 \cdot 10^{-12}$ F/m, $c = 2.997 \cdot 10^8$ m/sec

- for a 2 frequency differential phase path measurement
- $\Delta\Phi = (\varepsilon / c f_1 f_2^2)(f_1^2 - f_2^2) \int N \, dS$
  note that the result may exceed 2π and have ambiguities

  now let $f_1 = n_a f_0$, $f_2 = n_b f_0$, n_a and n_b integers
- Then TEC = $\int N \, dS = [\Delta\Phi \, n_a n_b^2 f_0 \, c / \varepsilon \, (n_a^2 - n_b^2)]$

- Thus total electron content and its variations are measured using differential phase, a measurement requiring two phase coherent signals
- Ambiguity resolution may be possible by using coarse & fine measures of $\Delta\Phi$

CUBEACON – Past vs Present Technology – improved SWAP

- Past Beacon apparatus for example: Hilat / Polar Bear -- 4 Kg 20·20·20 cm, 20w

  not including antenna

- Present beacon expectations – 0.4 Kg 8·8·8 cm, 8w

- The expected reduction in mass and volume by a factor of 10 and power by a factor of almost 3 is mainly due to these factors:
- Surface mount parts and multilayer PCBs with new RF PC materials that yield smaller designs
- Integrated circuit phase locked loop (PLL) components that operate at low power and enable greater flexibility in design
- Class-E RF amplifiers with new more capable transistors to improve DC-RF conversion efficiency
- Modern DC-DC converters that are more efficient and robust
- FPGA/CPLDs which facilitate complex logic and state machines with low power and size

- If needed, hi-rel radiation hardened parts that are equivalent to COTS parts are available for evaluation, design and flight hardware fabrication

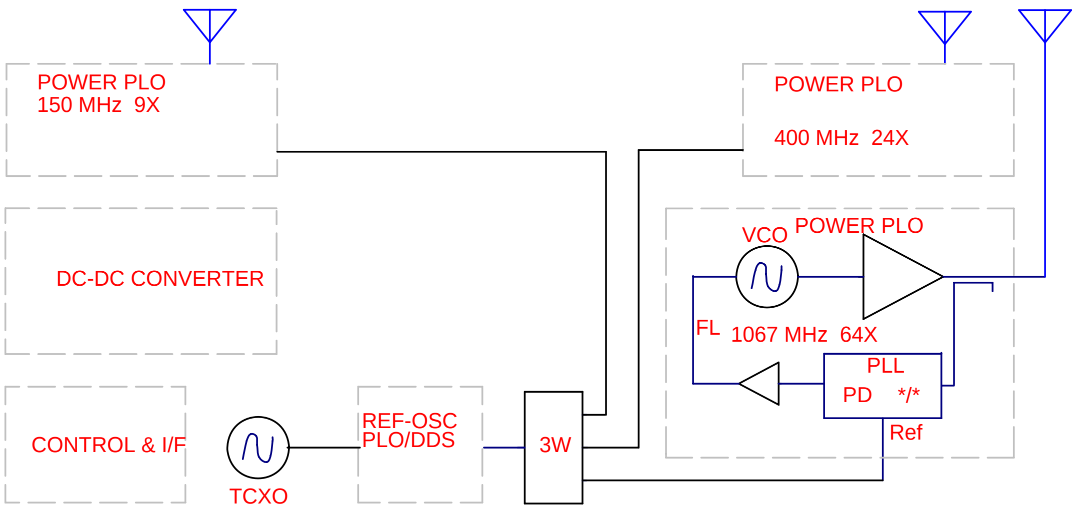
CUBEACON – System Frequency and Power Plans

- One wants the highest frequency to serve as a phase reference so as to be little disturbed by ionospheric perturbations that are commonly seen – L-band at least
- Lowest frequency to provide sensitive TEC and scintillation measure – VHF
- Middle range to provide TEC ambiguity resolution and redundancy – UHF
- Measurements may be L-V, U-V, or L-U
- Existing ground equipment working with 150-400 plan or 150-400-1067 plan
- Slight offset from CERTO, Transit, COSMOS would give feasible plan,
  doppler separation useful

- For ground-based receivers using low gain antennas, a minimum snr of order 30 dB is desired in a bandwidth of 250 Hz in order to measure ionospheric scintillation
  assuming a 600-800 Km LEO situation, then
- Power levels of 1-2 watts are needed for the CW transmissions, require licensing
- Higher gain ground antennas yield better measurements at the cost of complexity

CUBEACON – Basics of a CubeSat beacon instrument

- Block diagram showing one possile configuration of a beacon circuits
- A basic standard oscillator (10.000 MHz)
- Reference oscillator enables easy offset (f_0 = 16.666 MHz)
- PLOs comprising low power VCO, high efficiency amplifier and IC PLL (low power) to generate $9f_0$, $24f_0$ and $64f_0$
- Power, control and status monitoring support circuits



CUBEACON – Power PLOs, Phase Detectors, Loop Filters, PLL chips

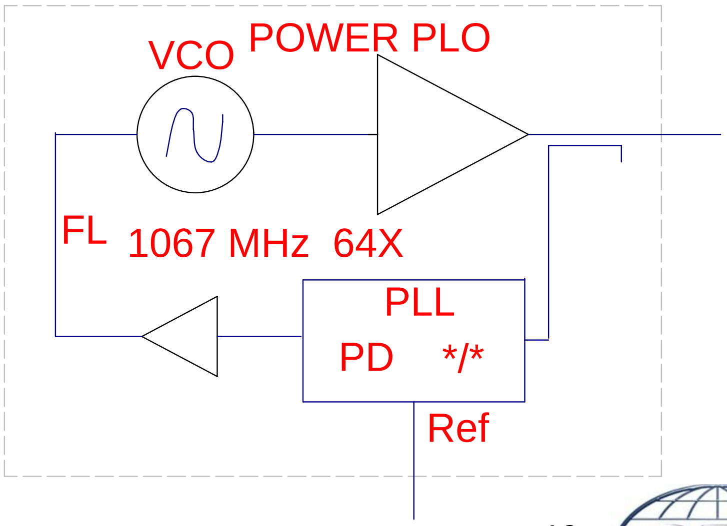
- Stable high Q low power VCO, varactor tuning, limited range

  Low phase noise, heritage design

- PLL chip, n-integer design, SOS fabrication, same for all PLOs
- Reference input 16.666 MHz for Power PLOs,

  10 MHz for Reference Generator, low level

- Output amplifier, Class-E, high efficiency and inside the loop
- Active loop filter, level shift and range control



CUBEACON – Efficient RF Amplifiers

- To be useful in a CubeSat environment and attractive as an improved instrument increased efficiency is benficial – therefore Class-E power amplifiers are advocated.

- Class-E RF amplifiers are believed to deliver the highest practical efficiency (of order 75-85%)

- Demonstrated designs for units at frequencies beyond 1 GHz and at power levels of 1w order and much larger.

- Appropriate output levels are approximately 1w at VHF, UHF with 2w at L-band – Expected DC power required ≈ 6w for the amplifiers alone
- Representing the largest part of power requirement

CUBEACON – Oscillator issues

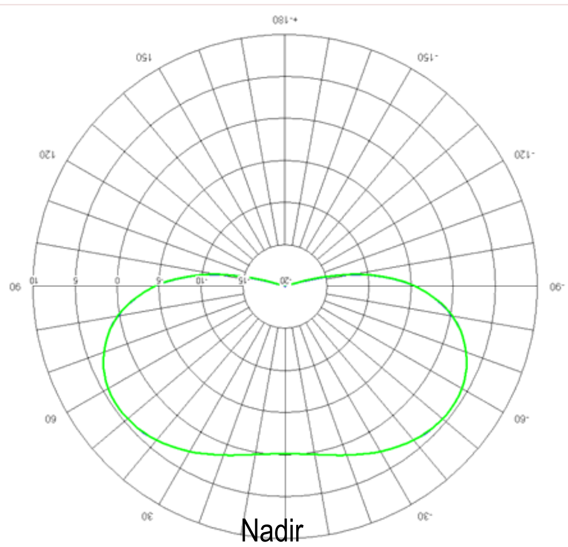
- For an ionospheric measurements beacon oscillator stability is not a large issue – a common TCXO will suffice
- Differential phase measurement cancels effects of oscillator drifts
- Drift only needs to be small in comparison to expected Doppler shift
- CubeSat beacon TCXO can be small, low power, low cost

- If instead the beacon is used for navigation via Doppler tracking, as for the TRANSIT system, then maximum stability is required over the tracking period. Probably an ovenized oscillator is needed.

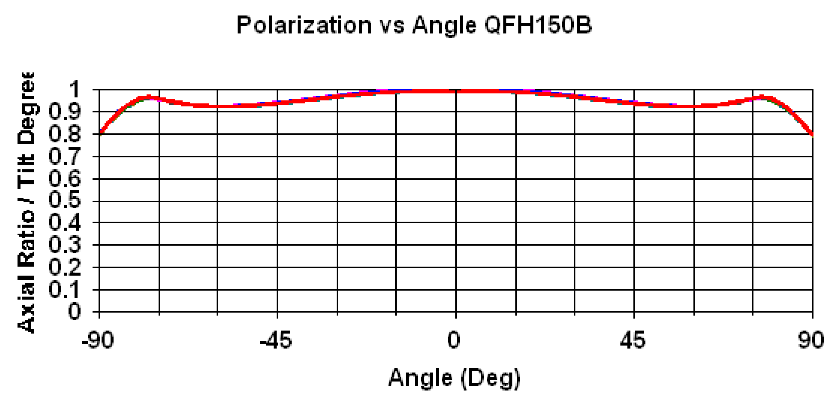
- By contrast, for hi-rel, long life missions redundant rad-hardened units are indicated -- special crystal choice & processing, high cost

CUBEACON – Antenna Matters

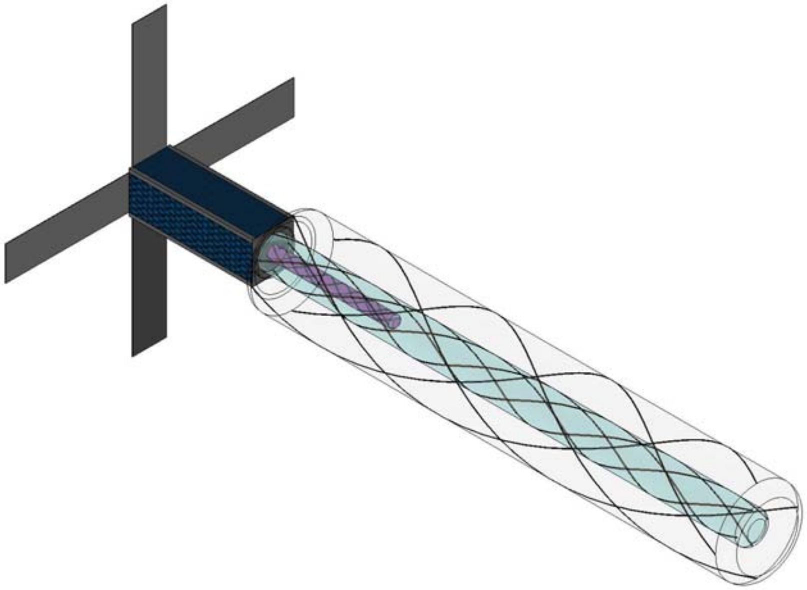
- The most desirable design has smooth pattern with circular polarization at all angles off nadir and pattern gain to compensate for range to the receiver – for all rotational orientations
- Beacon antenna reqirement is more stringent than ordinary communications antenna – broad, smooth
- Requires only nadir directed antenna on spacecraft, 3-axis stability not needed
- Best known design is the quadrifilar helix (QFH), gain, pattern and polarization are good
- QFH shows little effect due to interaction with spacecraft body or nearby devices
- Design heritage in many space applications including beacons, also commonly used in ground systems



A desirable antenna pattern



CUBEACON – Antenna Concept



- Shown here: a 3U CubeSat with fold out solar panels and deployed CUBEACON antenna
- VHF QFH needs 120 cm length and 20 cm diameter for useful pattern
- UHF QFH may nest inside at smaller 7.5 cm diameter and 90 cm length
- L-band antenna is possible at 7.5 cm diameter with shorter axial length
- UHF and L-band antennas are nested inside VHF
- Entire antenna structure fabricated on an insulating film (mylar or similar)
- Held in place and deployed by internal plastic semicylindrical columns spooled out from the body of the CubeSat – or other similar design
- Estimated pre-deployed volume 300 cm^3

HILAT / Polar Bear UHF L-band antenna

CUBEACON – Plans for the future, opportunities & objectives

- With good fortune it may be possible to develop an experimental beacon as described here to provide a test of devices and ideas not previously applied.

- Through proof of the new parts and application of existing heritage designs an improved beacon instrument with a higher technology readiness level (TRL) will result.

- An objective is to launch an experimental beacon on a 3U CubeSat bus (or larger spacecraft) into LEO as the opportunity arises
- Alternately test the equipment in a sub-orbital flight.

- Additional needs may also be served simultaneously by combining other apparatus with the ‘experiment’

- The design and fabrication of a high reliability operational style of instrument could proceed in parallel using the proven and/or to-be-proved techniques.

CUBEACON – Summary of the Main Points

- Beacon satellites are useful sensors of ionospheric conditions.
- New technology permits reduced SWAP of the instrument package. The antenna remains an issue with respect to size and deployment.
- A simple beacon may be developed for experimental tests in as little as a 3U CubeSat.
- Besides experimentally testing the beacon design ideas and materials, a beacon mission could provide other useful service.
- A deployable spacecraft antenna of nested quadrifilar helix design that would have the best possible antenna pattern is feasible for CubeSat use .