Laboratory Test of Vibration of Micro/Nano Satellite for Environment Test Standardization

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Background

- Micro/Nano satellite: Low-cost and fast-delivery using COTS.
- Existing testing standard not suitable for micro/nano satellites.
- The unit QT(Qualification Test) for large/medium satellite require too many margins.
- Needs to Define an adequate level of the unit test level.

- KIT initiated NETS (Nano Satellite Environment Test Standardization) project in 2011.
- Proposing affordable and reliable tests to the space community.
- Various environment tests according to NETS projects.
- Basic research- QT level vibration test.

Unit QT level strategy

- Existing QT- too much margins
- QT-guarantee design for space
- Products- no test history

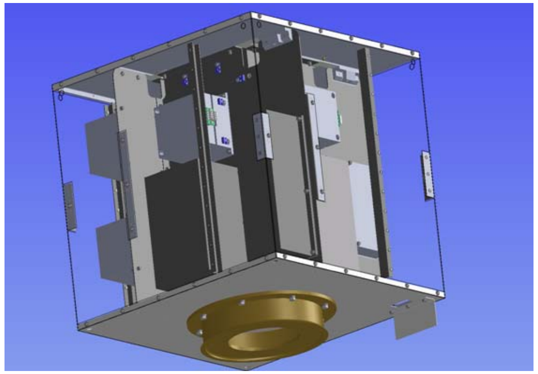
- Unit QT level in this standard - give minimum assurance
- Buyers get minimum assurance
- Customer may test again to their specification

Approach

- Statistics of experimental data
  - 20-300Hz : Statistics of various satellites
  - 300-2000Hz : Vibration test measure at various internal points
- Amplification factor of base vibrations
- Identify the minimum amplification factor
- Propose Unit QT level by multiplying PSD by AF.

Experimental System

Outline of vibration test



- Test article: Dummy satellite

(the Hodoyoshi-3 satellite AT test data was used for update dummy satellite test results)

- Size: 50cm x 50cm x 50cm
- Weight: 50kg class
- Vibration: Random vibration.
- Base acceleration: Adopted from SMC–S-016 (US Standard)
- Peak PSD levels and resonant frequencies were identified.
- To compute Normal tolerance limit, followed the ”Dynamic Environment Criteria”, NASA-HDBK-7005.

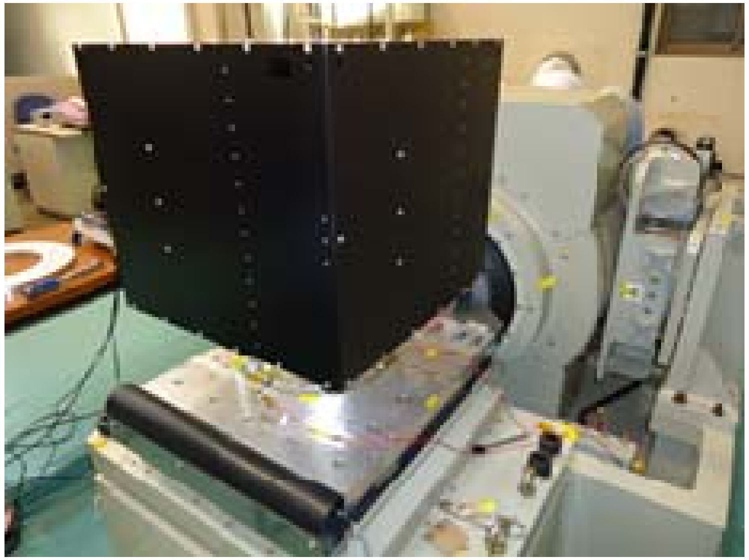
Test article

RF transmitter
PCU(Power Control Unit)
OBC(On board computer)
Battery

DM (Dummy masses) with heater inside

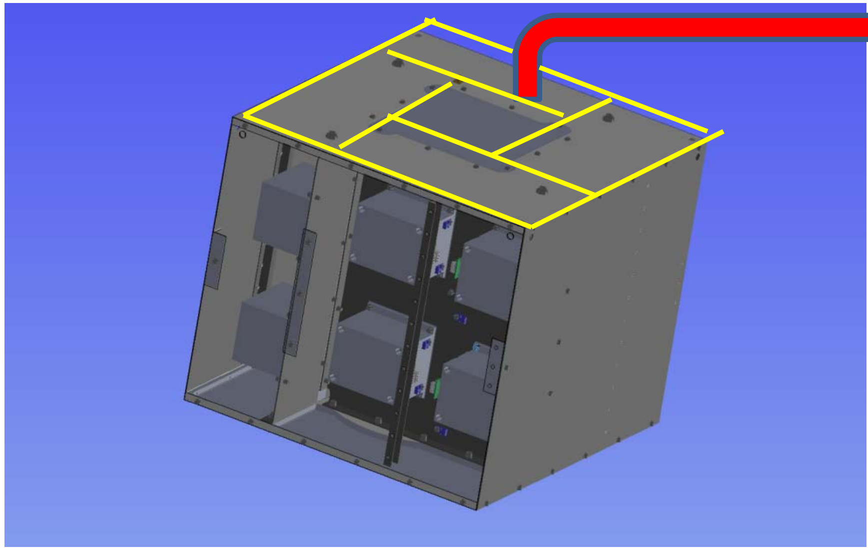
Structure - flight quality

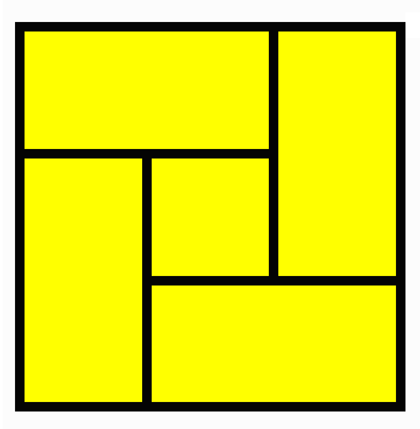
Dummy satellite
Size: 50cm x 50cm x 50cm



Hodoyoshi-3 satellite vibration test data are also used for update.

Test article





- ❖ "Four quarter tatami" - viewed from the top
- ❖ Seen as the popular layout of tatamis
- ❖ ***yo-jou-han***
  4.5 tatami room

www.uemura-tatami.com/archives/491

Test procedure

Satellite fixed to vibration machine
Accelerometers attached
Random vibration tests

Testing

↓

Peak PSD and resonant frequency
Finding vibration modes

Raw Data Analysis

↓

Statistical methods
to find Unit QT level

Final Statistical Analysis

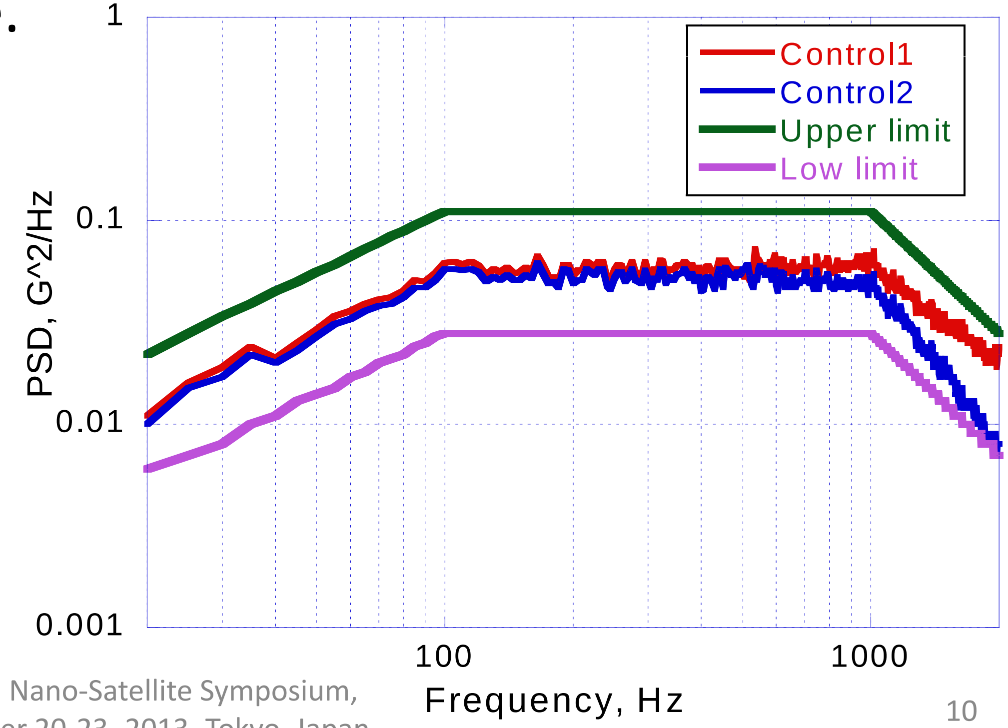
Random vibration spectrum profile

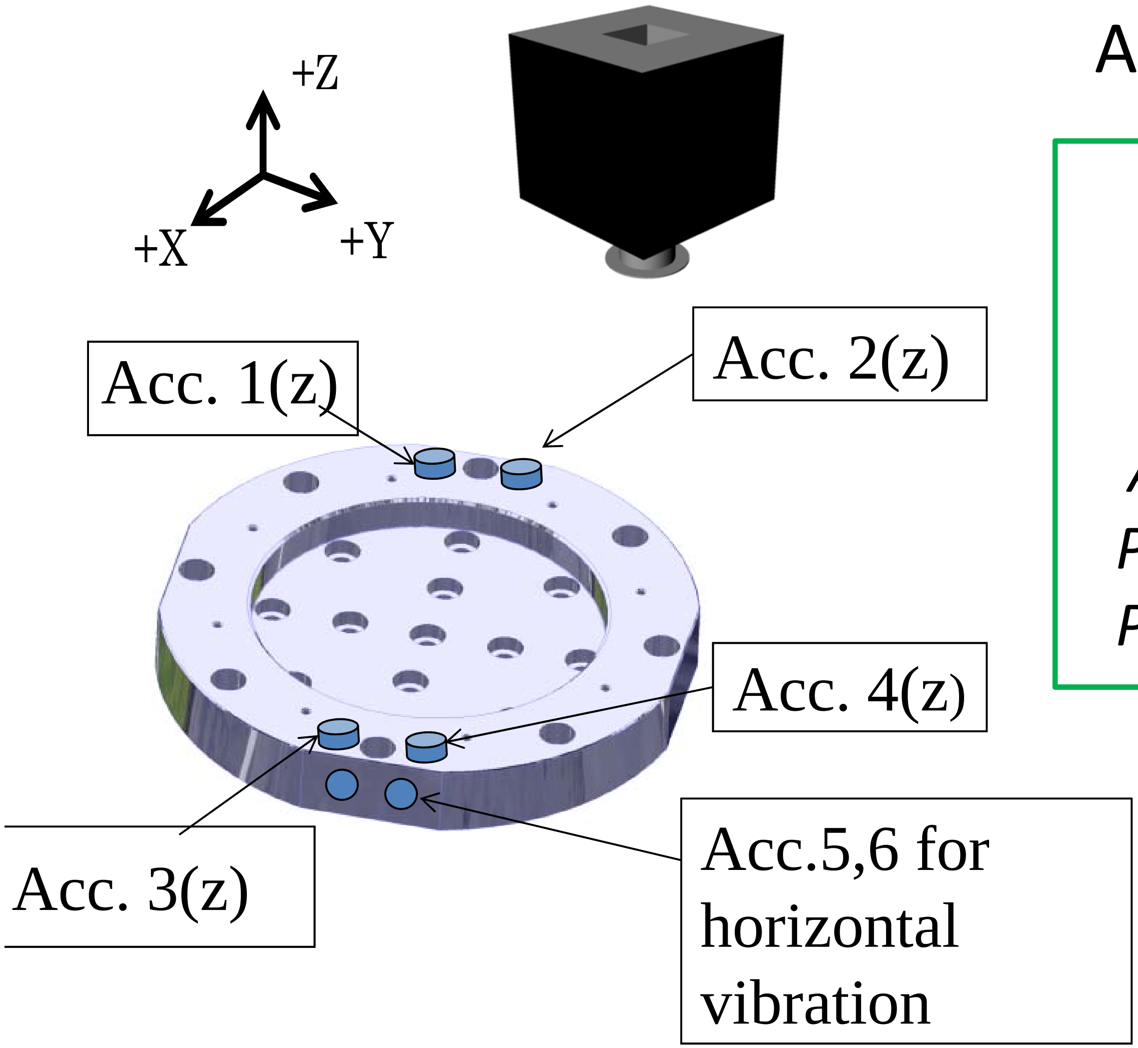
- Power Spectral Density (PSD) plot: Mean square acceleration per unit bandwidth
- Random vibration excites all the frequencies in a defined spectrum at any given time.

For the experiment:

Adopted from SMC –S-016

(US Standard)





Acc. : Accelerometers

Amplification Factor(AF)

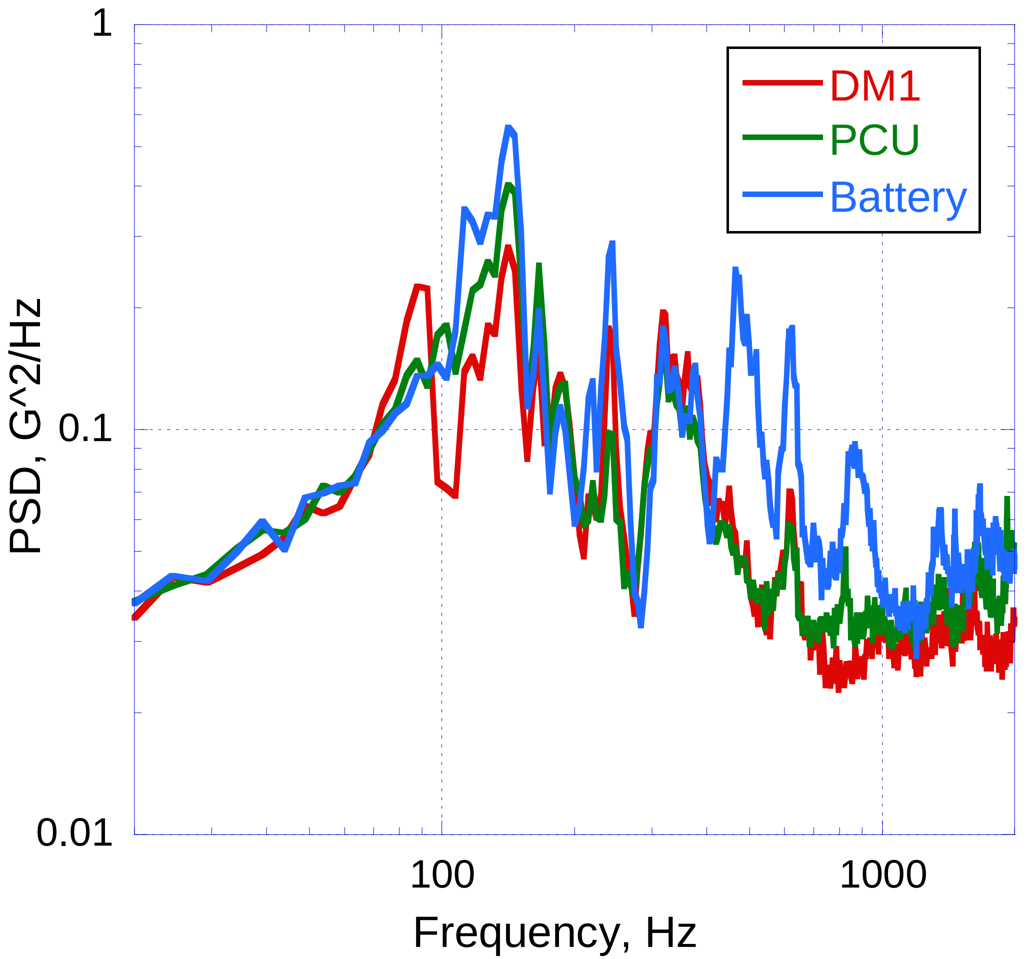
$$AF = \left(\frac{PSD_m}{PSD_b}\right)^{\frac{1}{2}}$$

AF : Amplification factor
PSD_m : Measured PSD value
PSD_b : Base level

If AF=1, no amplification
If AF>1, vibration amplified
If AF<1, attenuated vibration

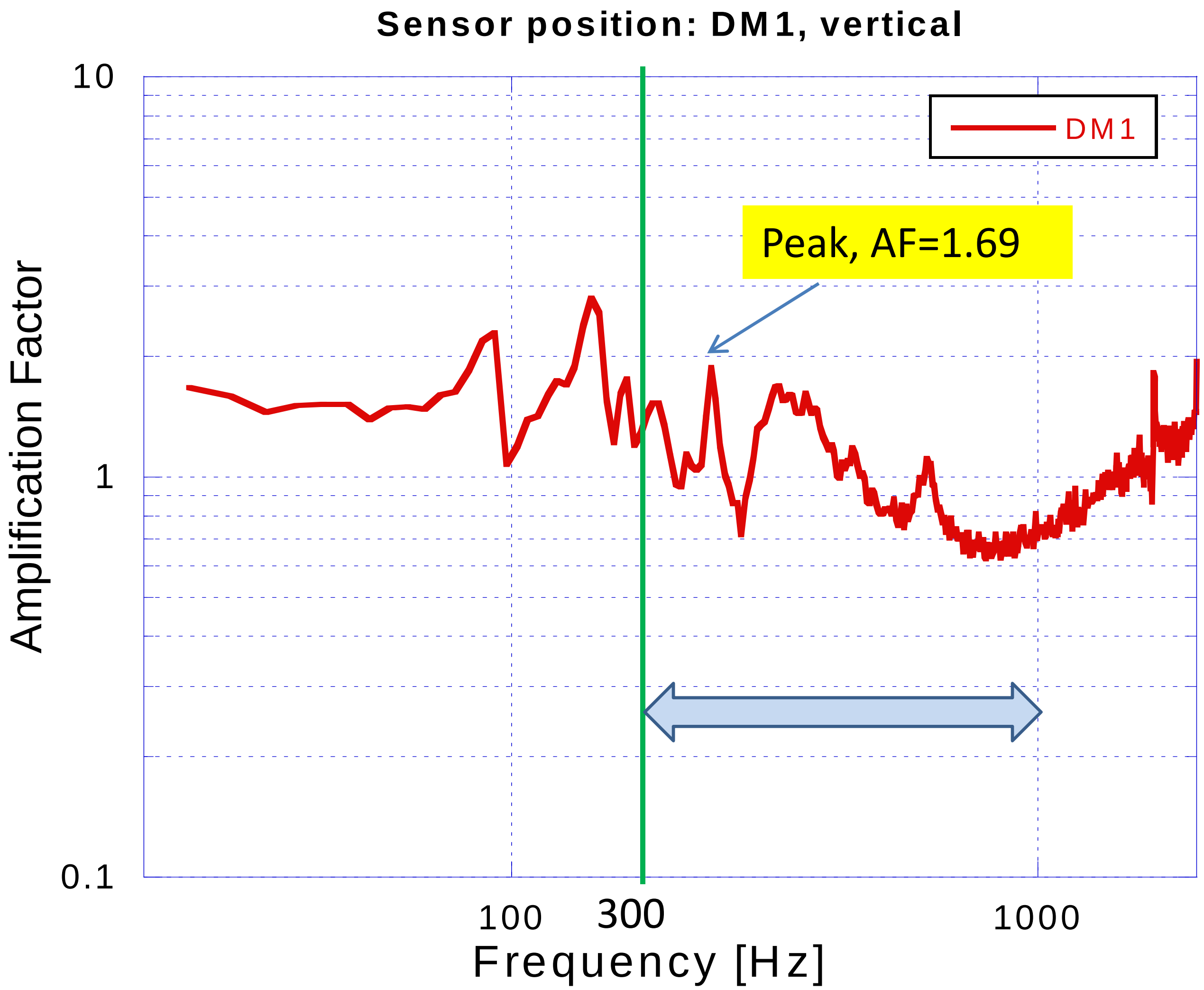
Test results and data analysis

Test result: PSD waveform



- Measured at 18 points
- Position: +x internal panel
- Base level: 9Grms
- Vibration : Vertical
- Accelerometer: z axis

Example of Test results: Amplification Factor



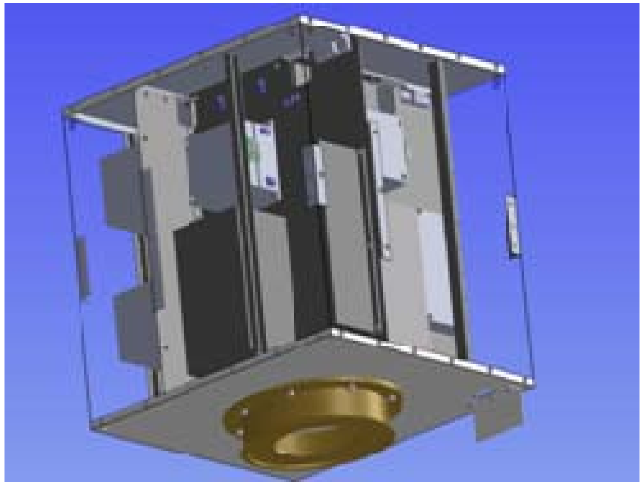
Test data statistics of dummy satellite(300-1000Hz)

- The **peak amplification factors** and **resonant frequencies** were deduced within three frequency ranges.
- Approximated these data by **lognormal distribution**.

	Resonant frequency[Hz]		
	Horizontal1	Horizontal 2	Axial direction
DM1	566.4	546.9	322.3
PCU	820.3	517.6	317.4
BATTERY	463.9	546.9	463.9
DM6	546.9	927.7	302.7
OBC	561.5	302.7	341.8
RF	546.9	493.2	307.6
DM4	551.8	542.0	302.7
DM2	571.3	498.1	302.7
DM5	561.5	546.9	302.7
DM3	571.3	498.1	302.7
DM9	537.1	996.1	302.7
DM7	566.4	961.9	302.7
DM10	537.1	493.2	356.5
DM8	566.4	659.2	302.7

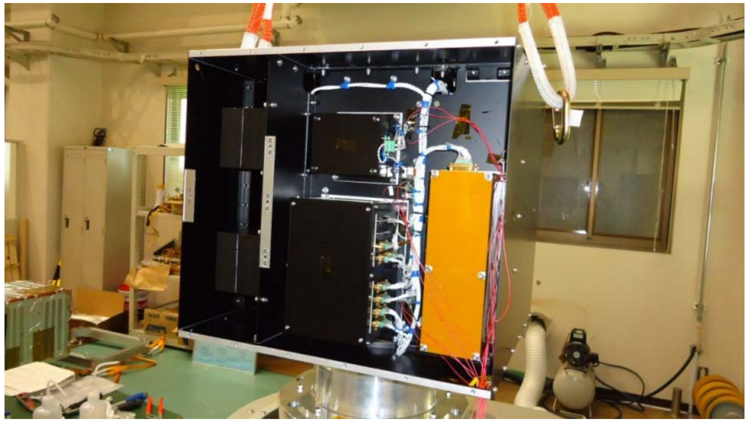
	Amplification factor		
	Horizontal1	Horizontal 2	Axial direction
DM1	1.35	2.83	1.69
PCU	2.50	5.97	1.54
BATTERY	4.31	1.85	2.18
DM6	2.40	2.31	1.00
OBC	5.50	9.86	0.72
RF	3.07	8.48	1.41
DM4	1.80	0.99	1.16
DM2	2.50	4.35	1.22
DM5	2.38	1.05	1.52
DM3	2.41	5.13	2.03
DM9	1.04	1.79	1.33
DM7	2.73	2.54	1.34
DM10	1.02	1.80	1.42
DM8	3.35	2.21	1.50

Vibration response modes



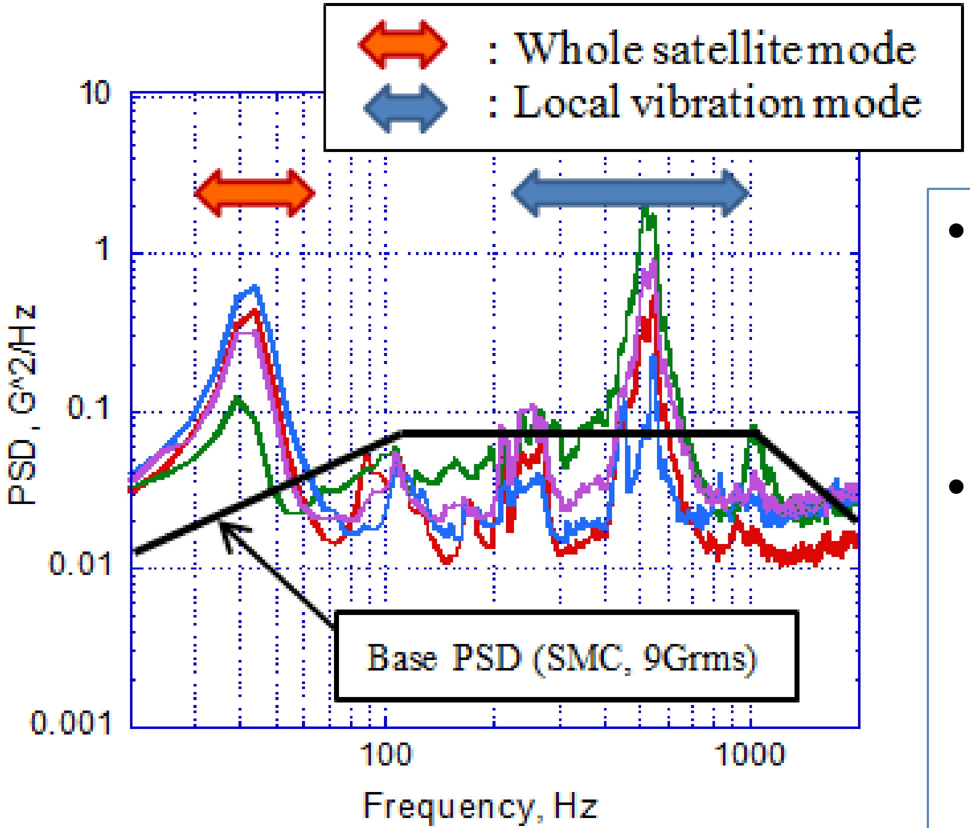
Local vibration mode
- 300-2000Hz
- Internal panel structure

300-1000Hz | 1000-2000Hz



Whole satellite mode
- 20-300Hz
- Entire satellite structure

Example of Vibration modes of micro/nano satellite

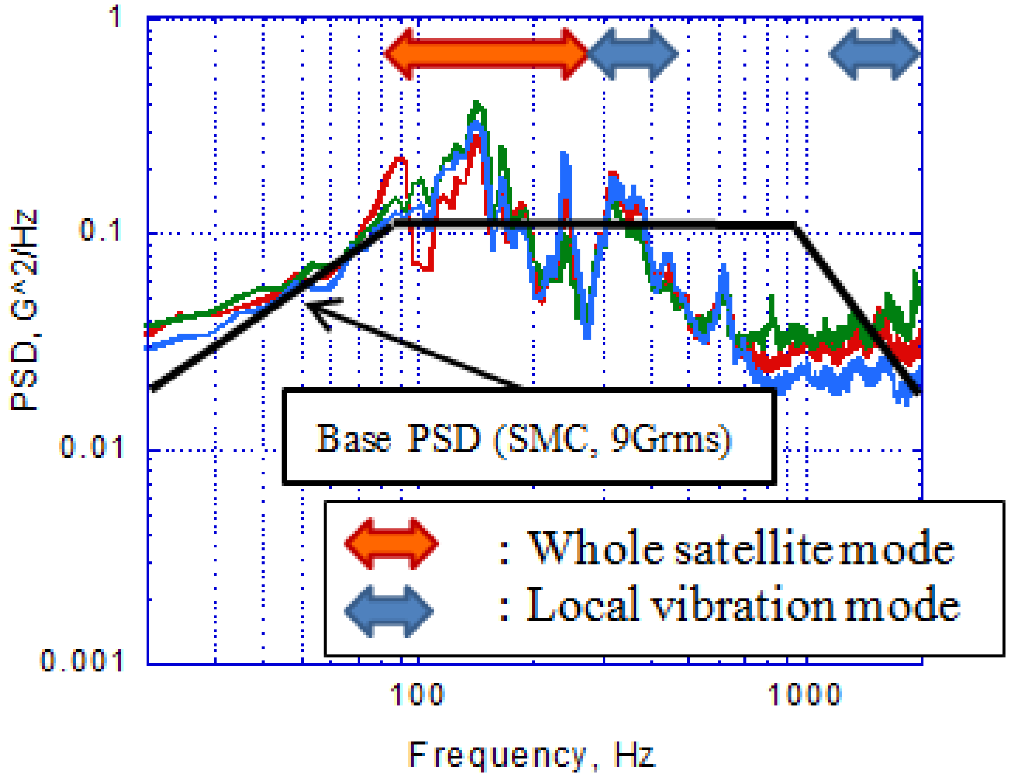


Horizontal Vibration response at internal panel

- Noticed two vibration modes: "Whole satellite mode" and "Local vibration mode".

- The measurement data were divided into three frequency range:
  1. **20-300Hz**: Whole satellite mode
  2. **300-1000Hz**: Local vibration mode
  3. **1000-2000Hz**: Local vibration mode

Vibration modes of micro/nano satellite



Vertical Vibration response
at internal panel

"Local vibration mode" due to mostly internal panels arrangement

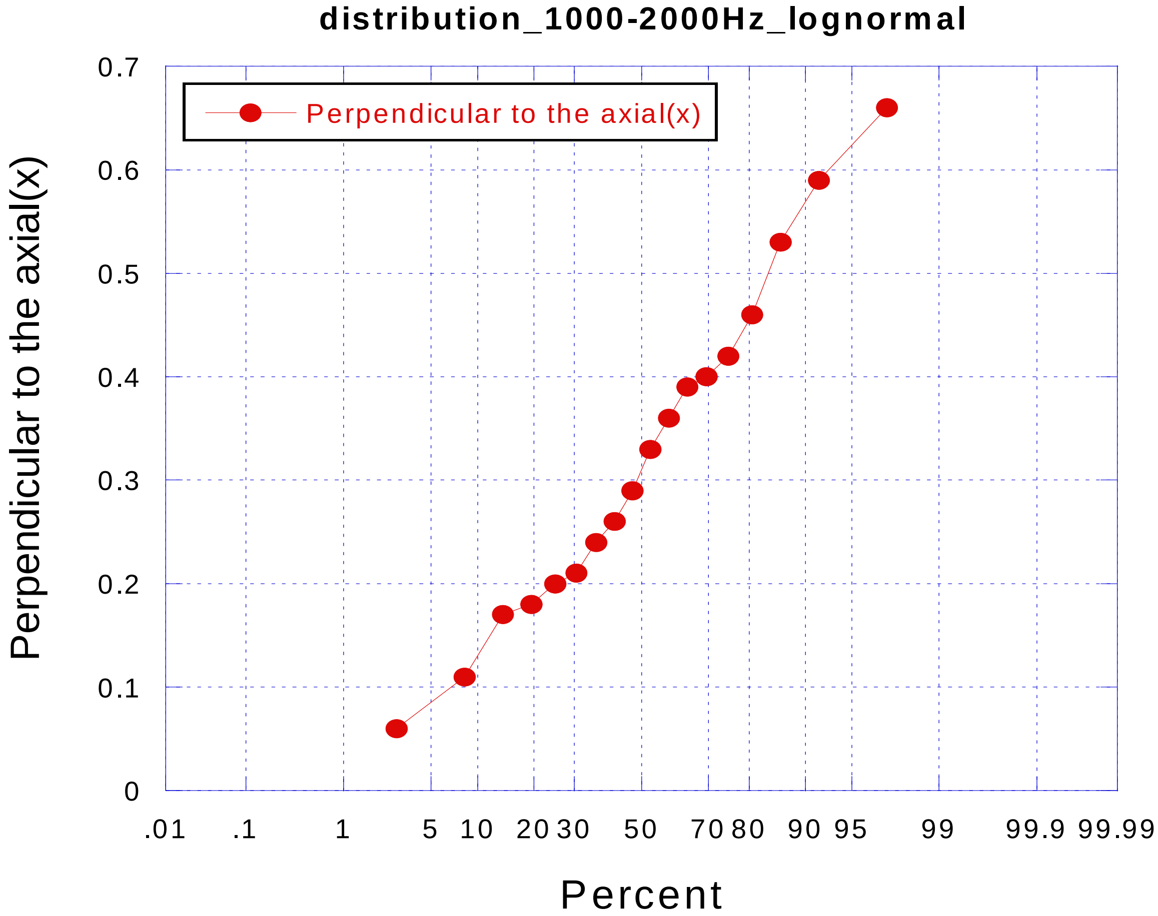
Statistical method to deduce Normal tolerance limit

- To compute Normal tolerance limit, followed NASA methodology: NASA-HDBK-7005
- The Handbook says:

  - *"there is evidence that the logarithm of the spectral values for any motion parameter describing the response from one to another have an approximate normal distribution"*
  - *"The spatial distribution of structural response spectra in a specific frequency resolution bandwidth approximately fits a lognormal distribution".*

- Examined whether our test data follow normal or lognormal distributions.
- χ^2 (Chi squared) goodness of fit statistics were used to check normality.

Example of Goodness-Of-Fit normality



After evaluating normality, we decided to choose lognormal as the distribution of Amplification factor.

Normal Tolerance Limit(NTL) calculation

$$y = log_{10}\, x$$

$$NTL_y(n, \beta, \gamma) = \bar{y} \pm k_{n,\beta,\gamma}\, s_y$$

- x: data value (e.g. AF, frequency)
- $k_{n,\beta,\gamma}$: normal tolerance factor.
- n=18 and $k_{n,\beta,\gamma}$ =1.67 for tested data.
- 95/50 limit
- β=0.95, γ=0.50

Normal tolerance limit of amplification factor in logarithm of the dummy satellite in the range: 300-1000Hz

	Resonant frequency[Hz]		
	Horizontal (x)	Horizontal (y)	Vertical (z)
Average	566.4	586.5	320.9
Standard deviation	281	760.4	161
Lower value	97.3	-683	51.1
Upper value	1035.7	1856.4	589.8

	Amplification factor		
	Horizontal (x)	Horizontal (y)	Vertical (z)
Average	0.39(2.4)	0.49(3.1)	0.14(1.4)
Standard deviation	0.20(1.6)	0.28(3.1)	0.11(1.3)
NTL (Min)	**0.06(1.15)**	0.02 (1.05)	0.04(1.1)
NTL (Max)	0.72(5.25)	0.96 (9.12)	0.32(2.09)

- **1.15** : maximum value of minimum Normal tolerance limit among all direction.
- **1.15** was chosen as the unit QT level in the range: **300Hz and 1000Hz.**

Amplification factor, 20-300Hz

Satellite	normal		
	Horizontal x	Horizontal y	Axial direction
Satellite-A	8.2	10.4	8.0
Satellite-B	4.21	5.18	5.86
Satellite-C	6.52	5.75	7.56
Satellite-D	7.31	7.27	5.05
Satellite-E	5.73	6.92	3.39
Satellite-F	6.78	5.19	3.27

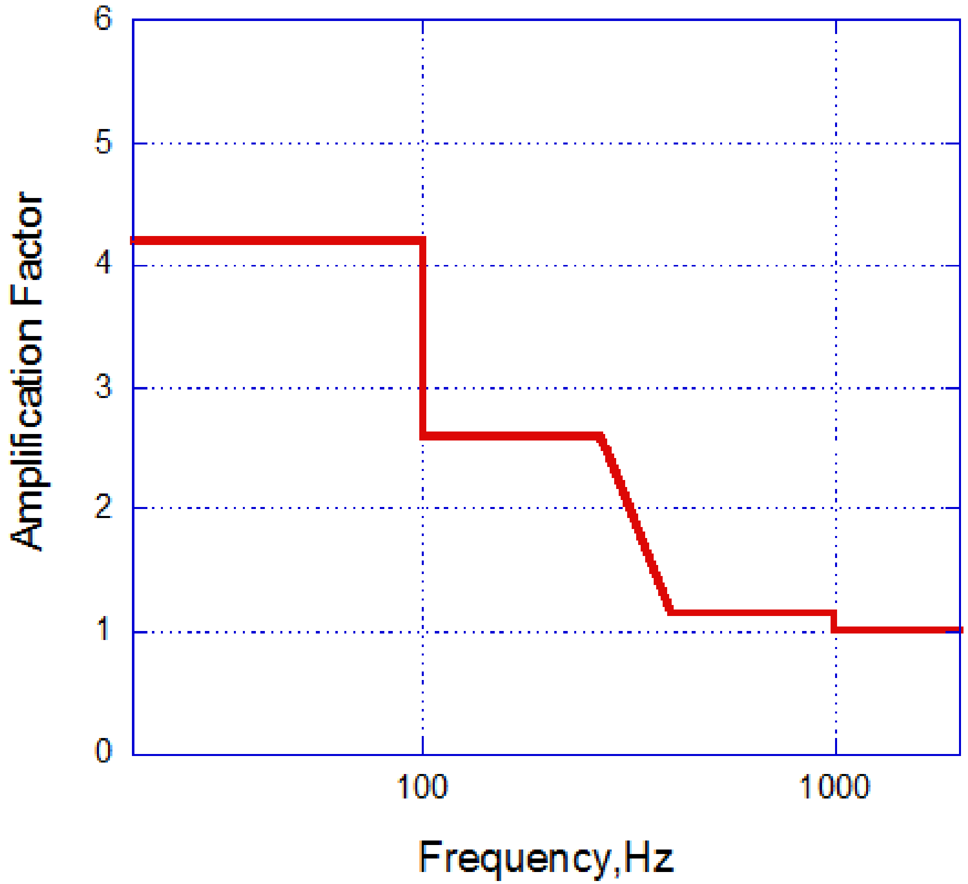
Normal tolerance limit of amplification factor in logarithm in the range: 20-300Hz (real values are shown in bracket).

	Resonant frequency [Hz]		
	Horizontal 1	Horizontal 2	Vertical
Average	54	49	172
Standard deviation	27	28	56
Lower value	6.7	0	74
Upper value	101.2	98	270

	Amplification factor		
	Horizontal1	Horizontal2	Vertical
Average	0.80 (6.3)	0.82(6.6)	0.72(5.2)
Standard deviation	0.10 (1.2)	0.12(1.3)	0.17(1.5)
NTL (Min)	0.62 (4.2)	0.61 (4.1)	0.42 (2.6)
NTL (Max)	0.97 (9.3)	1.03 (10.7)	1.0 (10)

- **4.2** : maximum value of minimum Normal tolerance limit among all direction.
- **4.2** was chosen as the unit QT level between **20Hz and 101Hz.**

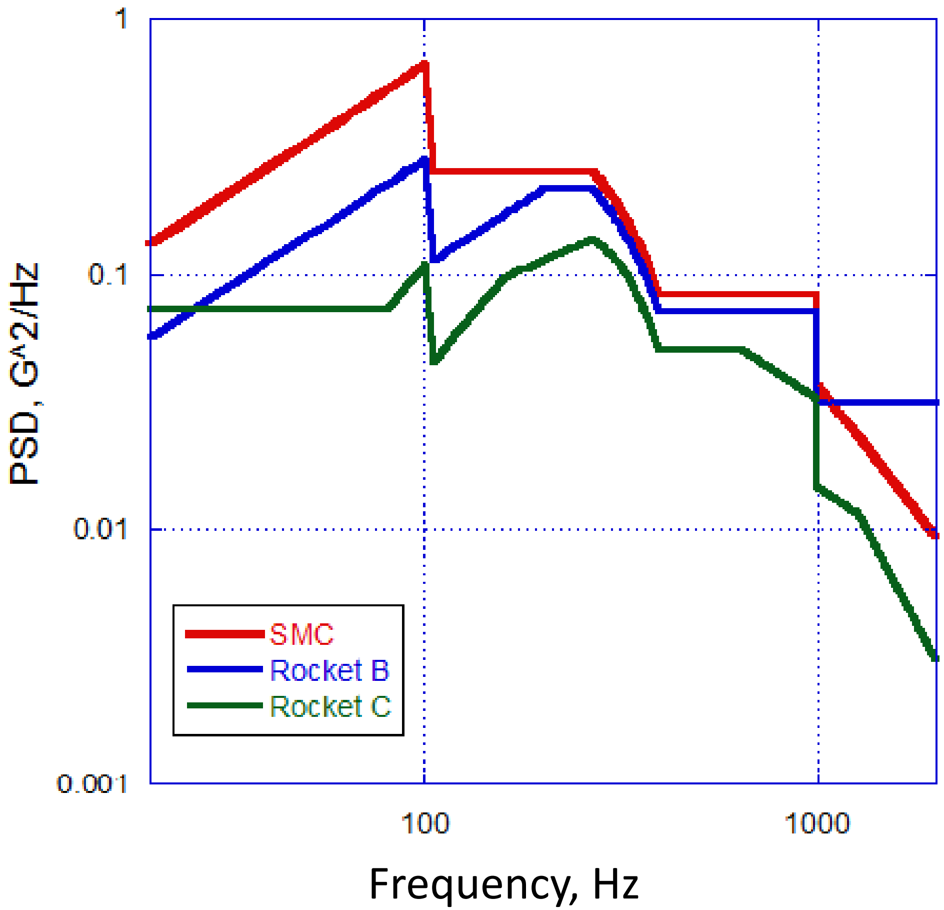
The amplification factor and resonance frequency range for unit QT test level (20-2000Hz)



- Results of three frequency ranges merged.
- Amplification factor of unit QT level between 20Hz and 2000Hz .

Unit QT level (20-2000Hz)

Unit QT level= PSD(AT level) x Amplification factor^2



RMS

- **SMC : 12.9Grms**
- **Rocket B : 11.8Grms**
- **Rocket C : 8.4Grms**

- Propose Rocket B as Unit QT level.

Conclusion

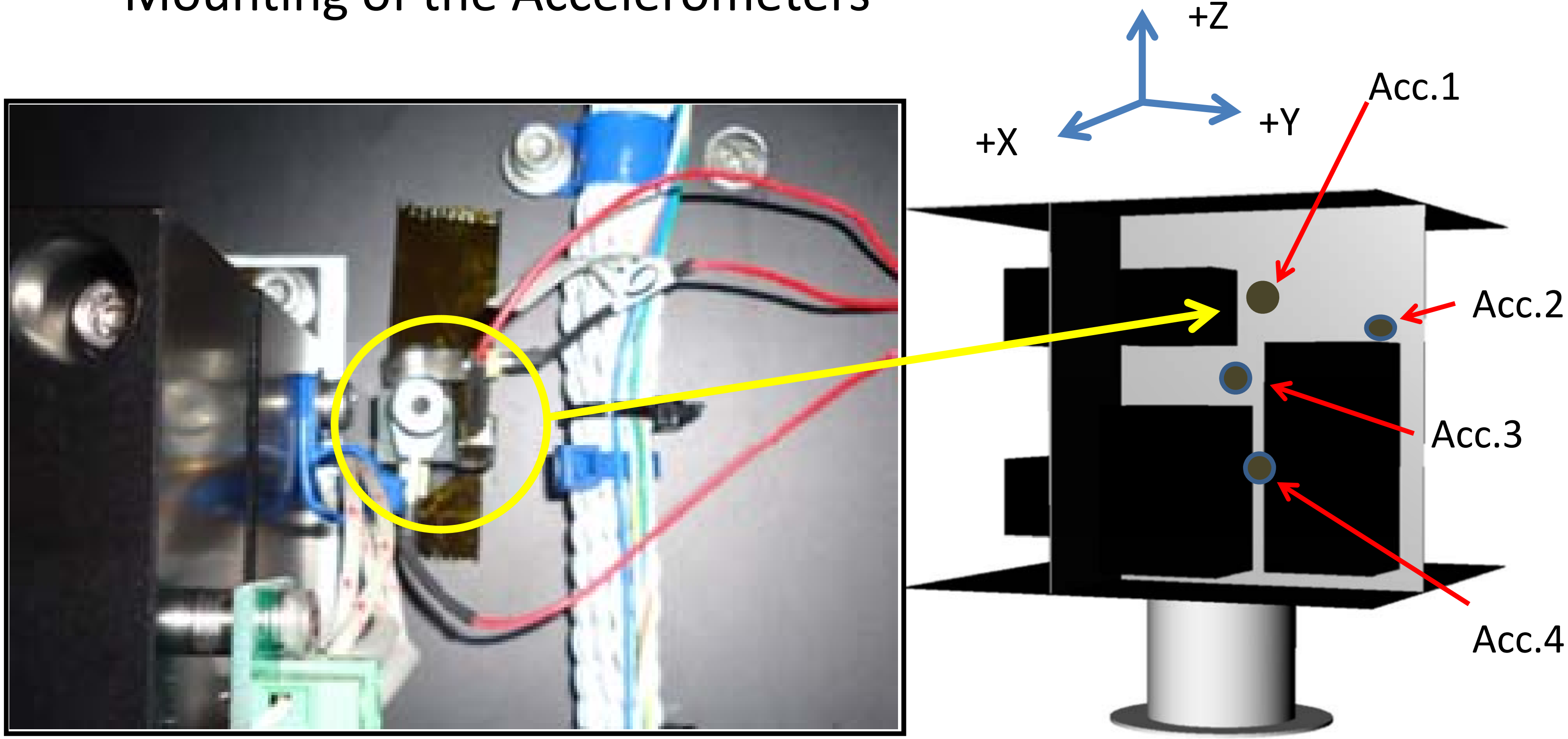
- Basic research has been carried out to find Unit QT level.
- Amplification factor and range of resonant frequencies were considered.
- Unit QT test level has been proposed.

Future work:

- Finite Element Analysis (FEA) of small satellites structures will be carried out to update experimental results.

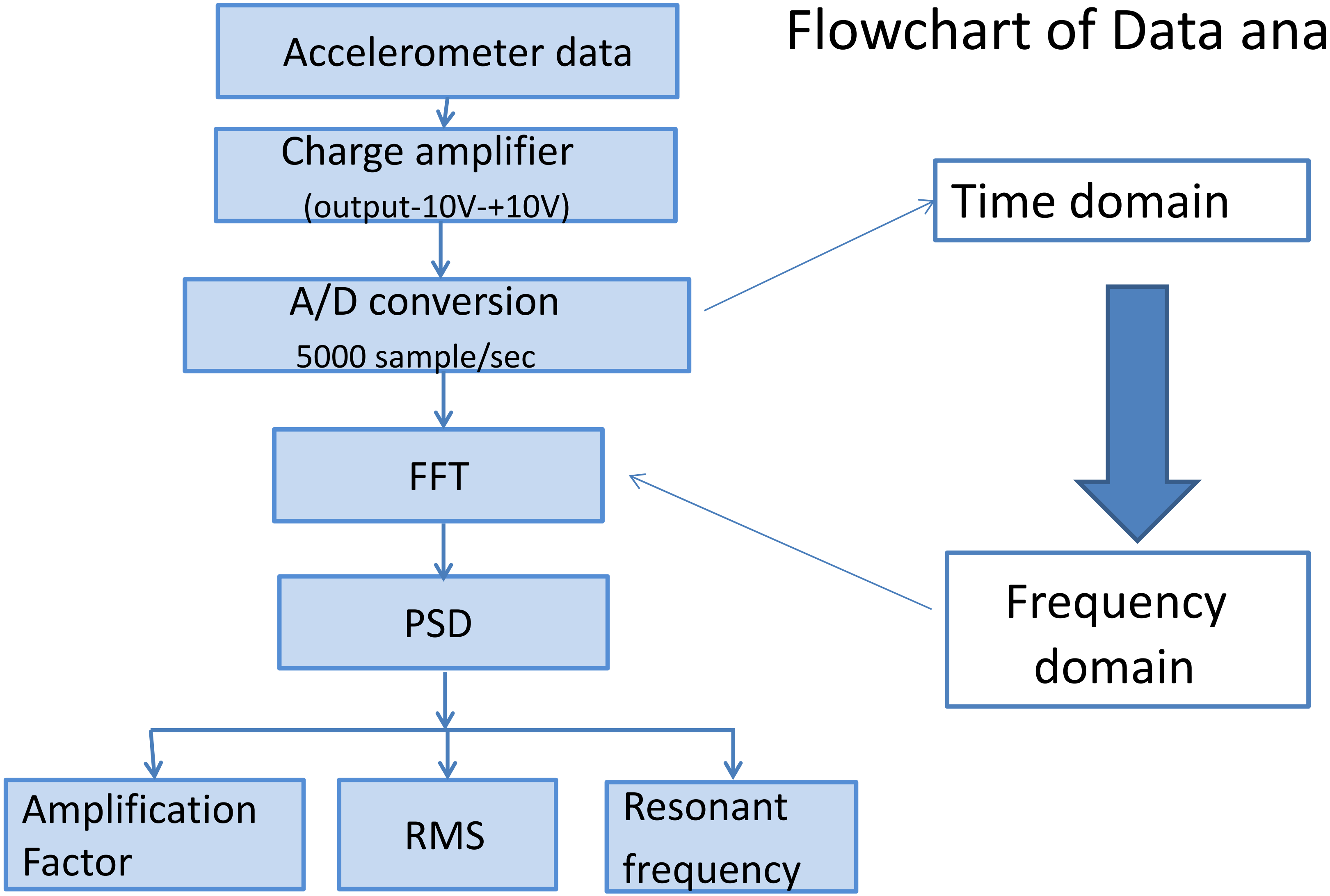
Appendix

Mounting of the Accelerometers



Accelerometers attached at positions of internal and external panels.

Flowchart of Data analyzing



Peak amplification factor, 1000-2000Hz

position	normal			lognormal		
	(X)	(Y)	Axial (Z)	Log(x)	Log(y)	Log(z)
DM1	2.27	1.07	1.83	0.36	0.03	0.26
PCU	3.36	1.44	2.07	0.53	0.16	0.32
BATTERY	2.86	1.42	2.60	0.46	0.15	0.41
DM6	1.72	2.17	1.76	0.24	0.34	0.25
OBC	1.96	4.35	2.94	0.29	0.64	0.47
RF	2.12	2.98	2.93	0.33	0.47	0.47
DM4	2.49	1.50	1.41	0.40	0.18	0.15
DM2	3.86	1.83	2.23	0.59	0.26	0.35
DM5	2.61	1.90	1.87	0.42	0.28	0.27
DM3	4.53	3.07	1.35	0.66	0.49	0.13
DM9	1.28	3.29	2.14	0.11	0.52	0.33
DM7	1.58	2.42	2.27	0.20	0.38	0.36
DM10	1.62	2.66	2.63	0.21	0.42	0.42
DM8	2.44	3.29	1.94	0.39	0.52	0.29

Normal tolerance limit of amplification factor in logarithm of the dummy satellite in the range: 1000-2000Hz

	Resonant frequency[Hz]		
	Horizontal (x)	Horizontal (y)	Vertical (z)
Average	1798.2	1798.2	1694.1
Standard deviation	864.7	1746.1	601.1
Lower value	354.1	-1117.8	690.3
Upper value	3242.2	4714.2	2697.9

	Amplification factor		
	Horizontal (x)	Horizontal (y)	Vertical (z)
Average	0.33(2.1)	0.32(2.1)	0.29(1.9)
Standard deviation	0.68(4.8)	0.70(5.0)	0.47(2.9)
NTL (Min)	**-0.81 (0.15)**	**-0.85 (0.14)**	**-0.49 (0.32)**
NTL (Max)	1.47(29.5)	1.49 (30.9)	1.07 (11.75)

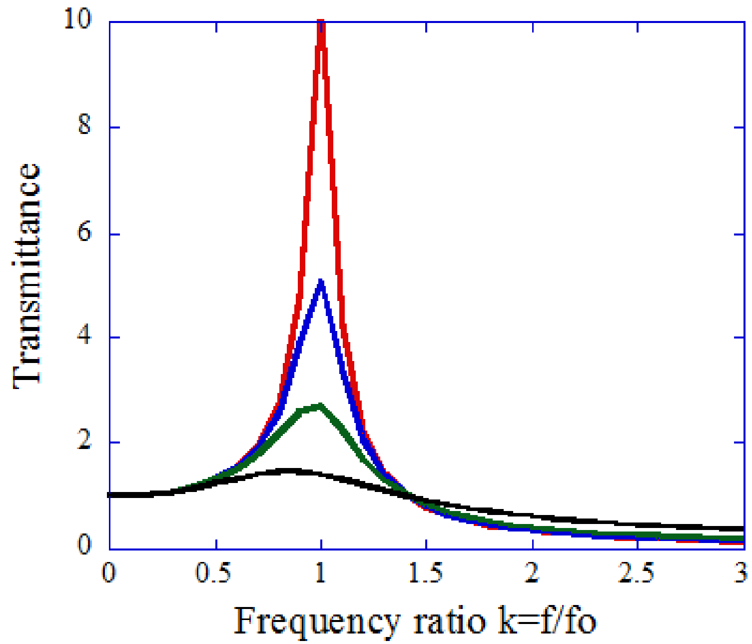
- **No amplification in 1000-2000Hz range.**
- **We simply take the amplification is uniform at unity between 1000Hz and 2000Hz**

Calculation of vibration transmittance apart from resonant frequency range

$$\tau = \sqrt{\frac{1+(2\zeta\kappa)^2}{(1-\kappa^2)^2+(2\zeta\kappa)^2}}$$

$$\kappa = \frac{f}{f_o}$$

$$Q \approx \frac{1}{2\zeta}$$



- *τ: Transmittance, ζ:* damping rate, *κ:* frequency rate, *f and* f_0*:* base and resonant frequency.
- In our case, transmittance is equal to the amplification factor.
- For calculating the gradient value from 270Hz to higher, amplification factor and frequency were extrapolated until the amplification factor became 1.15.
- The amplification became 1.15 at 390Hz. Assumed ζ=0.1.