CTBTO.ORG

CTBTO
PREPARATORY COMMISSION

COMPREHENSIVE
NUCLEAR-TEST-BAN
TREATY ORGANIZATION

Metrology in support of the Comprehensive Nuclear Test-Ban Treaty (CTBT)

N. Hermanspahn, CTBTO

- The Treaty
- Treaty Verification
- The International Monitoring System
- Radionuclide monitoring for CTBT
- Gamma spectrometry for aerosol measurements
- Xenon measurements in the IMS
- Summary

The Treaty

Article I: Basic Obligations

1. Each State Party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its jurisdiction or control.

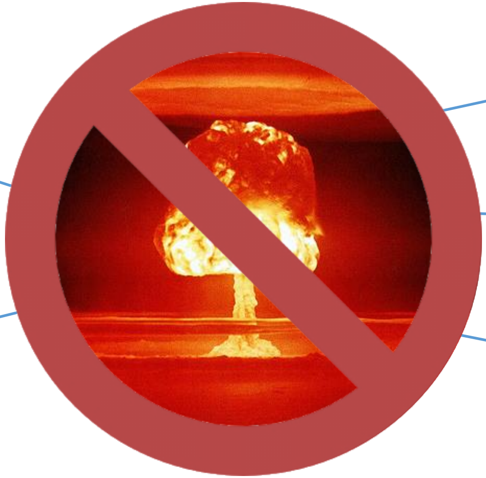
2. Each State Party undertakes, furthermore, to refrain from causing, encouraging, or in any way participating in the carrying out of any nuclear test explosion or any other nuclear explosion.

What is the Comprehensive Nuclear-Test-Ban Treaty (CTBT)?

The CTBT is an **international treaty** that **bans all nuclear explosions, by anyone, anywhere**

Effective nuclear non-proliferation (horizontal and vertical) and disarmament measure

Important step to a world without nuclear weapons



187 States have signed, 178 ratified;
Not yet in force !

Verification

International Monitoring System

On-site Inspections

Consultation/Clarification and
Confidence Building Measures

CTBT Verification Regime: Elements

International Monitoring System

337 facilities:

- Seismic
- Hydro-acoustic
- Infrasound
- Radionuclide, Noble gas, Laboratories

GCI & IDC

Consultation and Clarification

Right to clarify matters indicating possible non-compliance

On-Site Inspection

Conduct of on-site verification activities

Confidence Building Measures

Large chemical Explosions: Prevent misinterpretations and calibrate seismic IMS component

International Monitoring System

- Primary Seismic Stations (50)
- Auxiliary Seismic Stations (120)
- Infrasound stations (60)
- Hydroacoustic (11)
- Radionuclide (80)
- Noble gas systems (40)
- RN Laboratory (16)

Verification System Monitoring Technologies

Network >90% complete

Seismic

Listening underground

155/170 certified

Hydroacoustic

Listening under water

11/11 certified

Infrasound

Listening above ground

53/60 certified

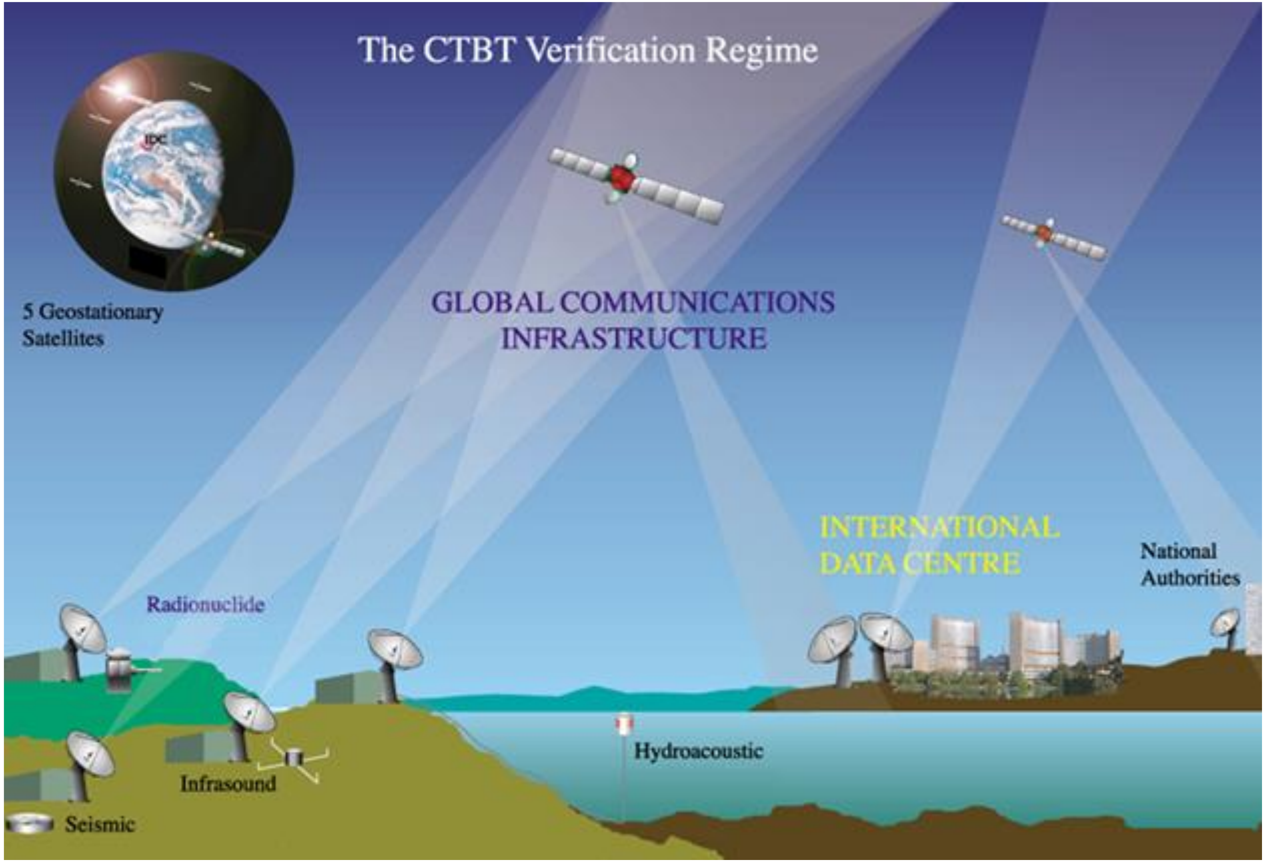
Radionuclide

Sniffing for radiation

87/96 facilities certified

- 73/80 RN Particulate **Stations** (26/40 add. Noble Gas Capability cert.)
- 14/16 Radionuclide **Laboratories**

GCI and IDC

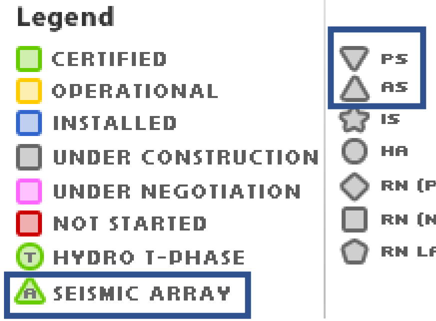

The CTBT Verification Regime
5 Geostationary Satellites
GLOBAL COMMUNICATIONS INFRASTRUCTURE
INTERNATIONAL DATA CENTRE
National Authorities
Radionuclide
Hydroacoustic
Infrasound
Seismic

Seismic Stations

COMPREHENSIVE NUCLEAR-TEST-BAN TREATY ORGANIZATION

IMS Seismic Network

- Primary Seismic Stations (50)
- Auxiliary Seismic Stations (120)
- Two types of Seismic Stations: stations with a single seismometer and arrays with several seismometers



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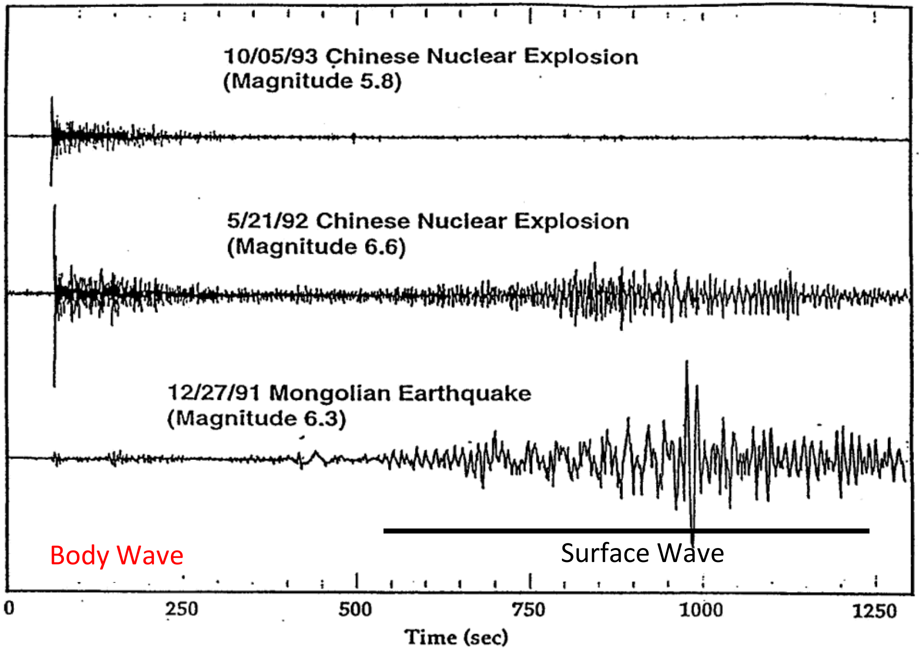
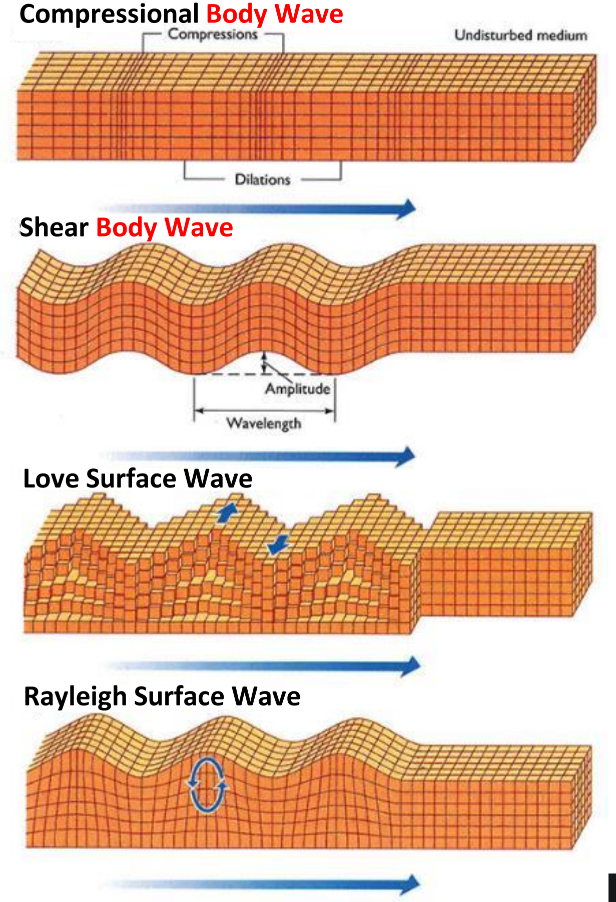
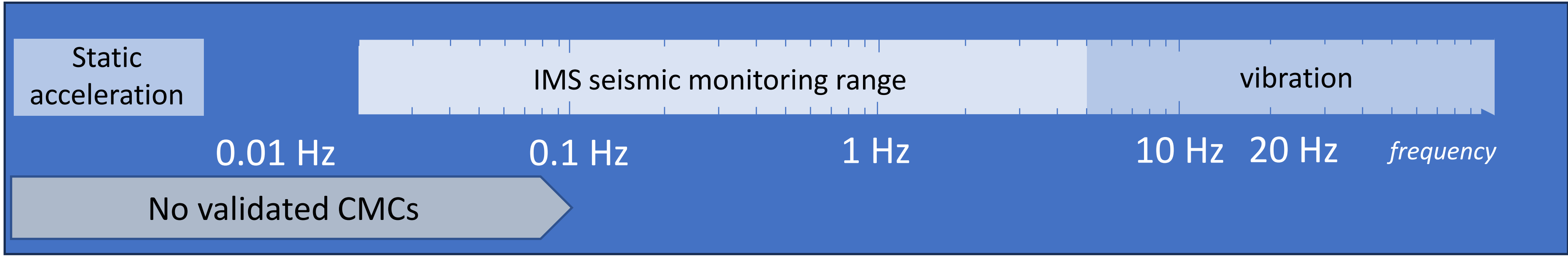
Earthquake or Explosion?

- Seismic stations detect signals from both natural and man-made sources
- Seismic signals recorded from (nuclear) explosions are characterized by a predominance of Body Waves





Metrology needs

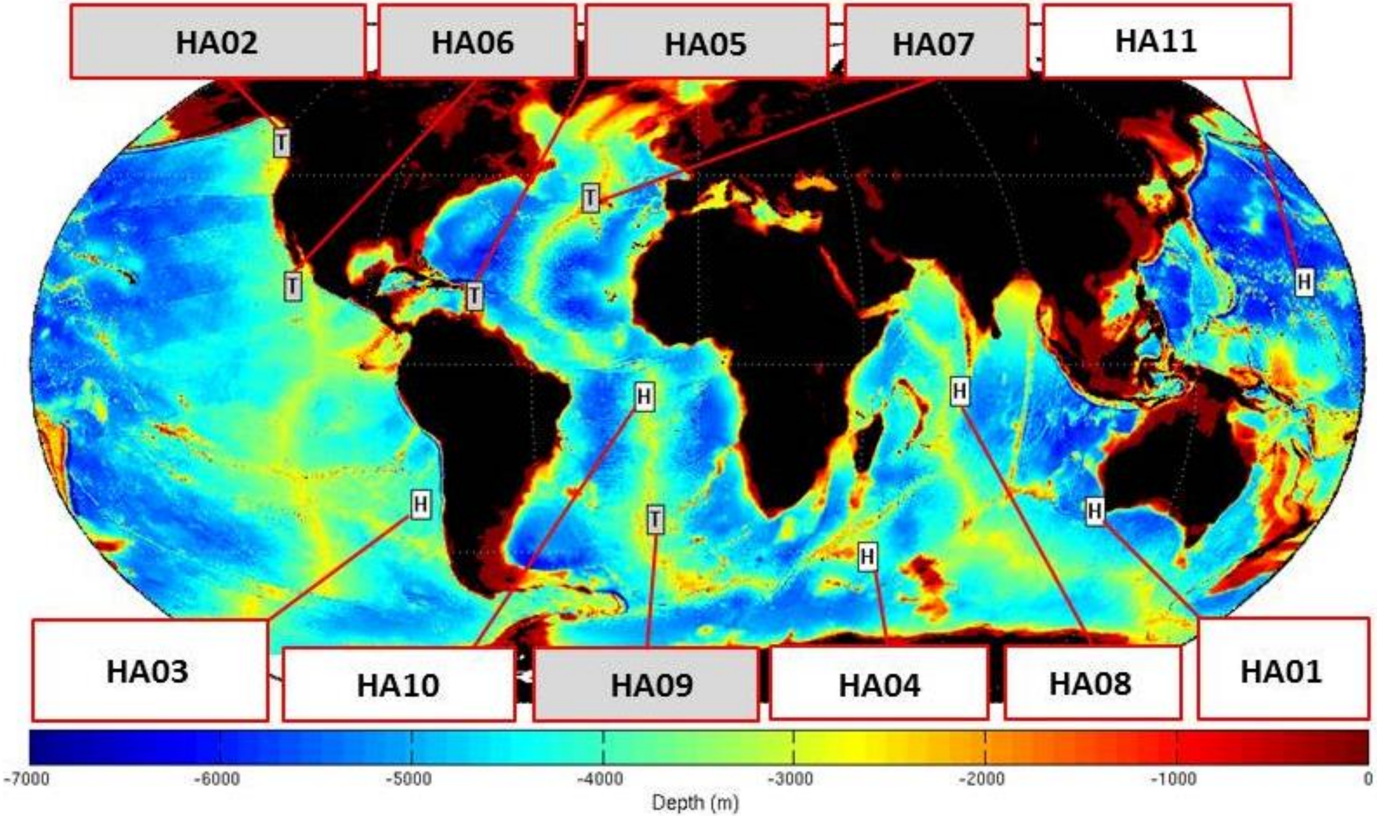


Hydroacoustic Stations

IMS Hydroacoustic Network

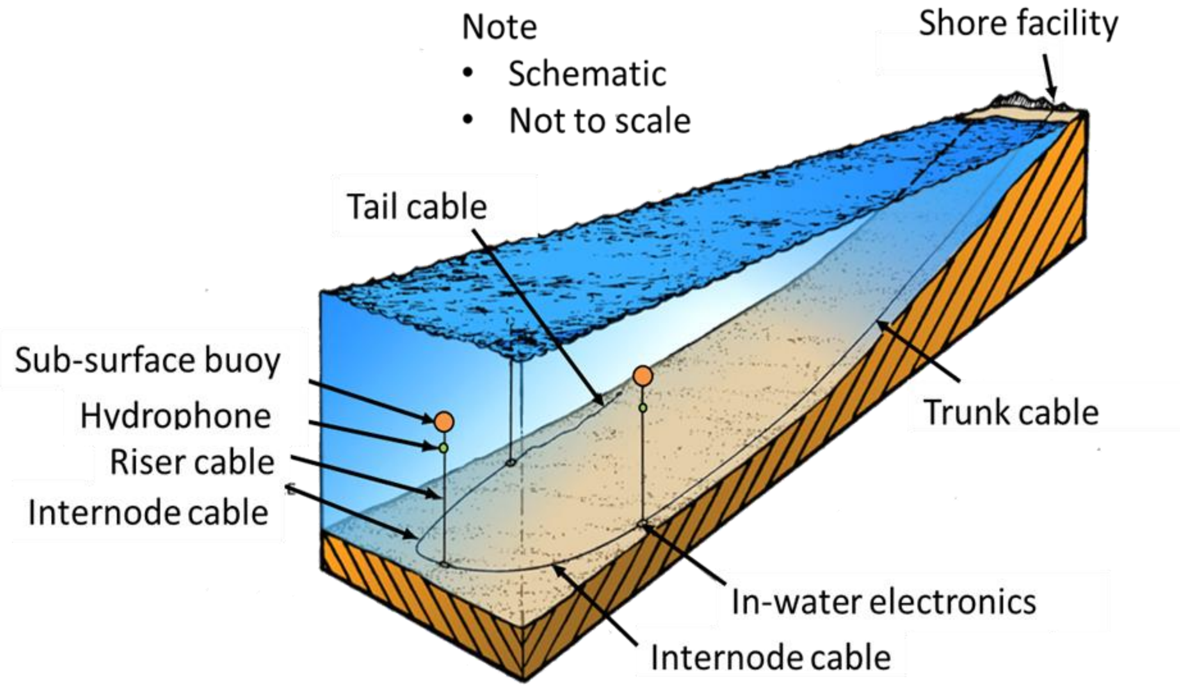
- Six hydrophone based HA stations

- Five seismometer based T-phase HA stations

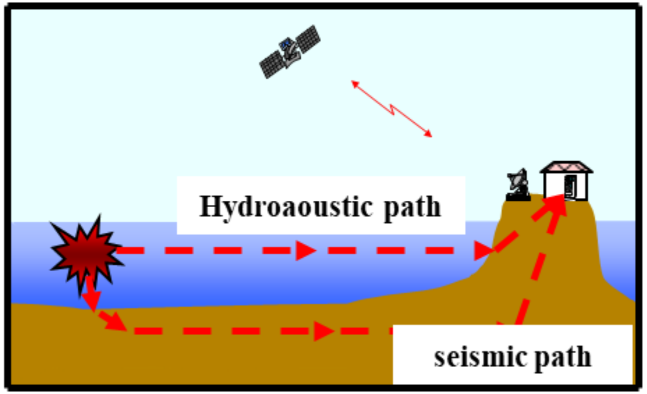


Hydroacoustic Stations

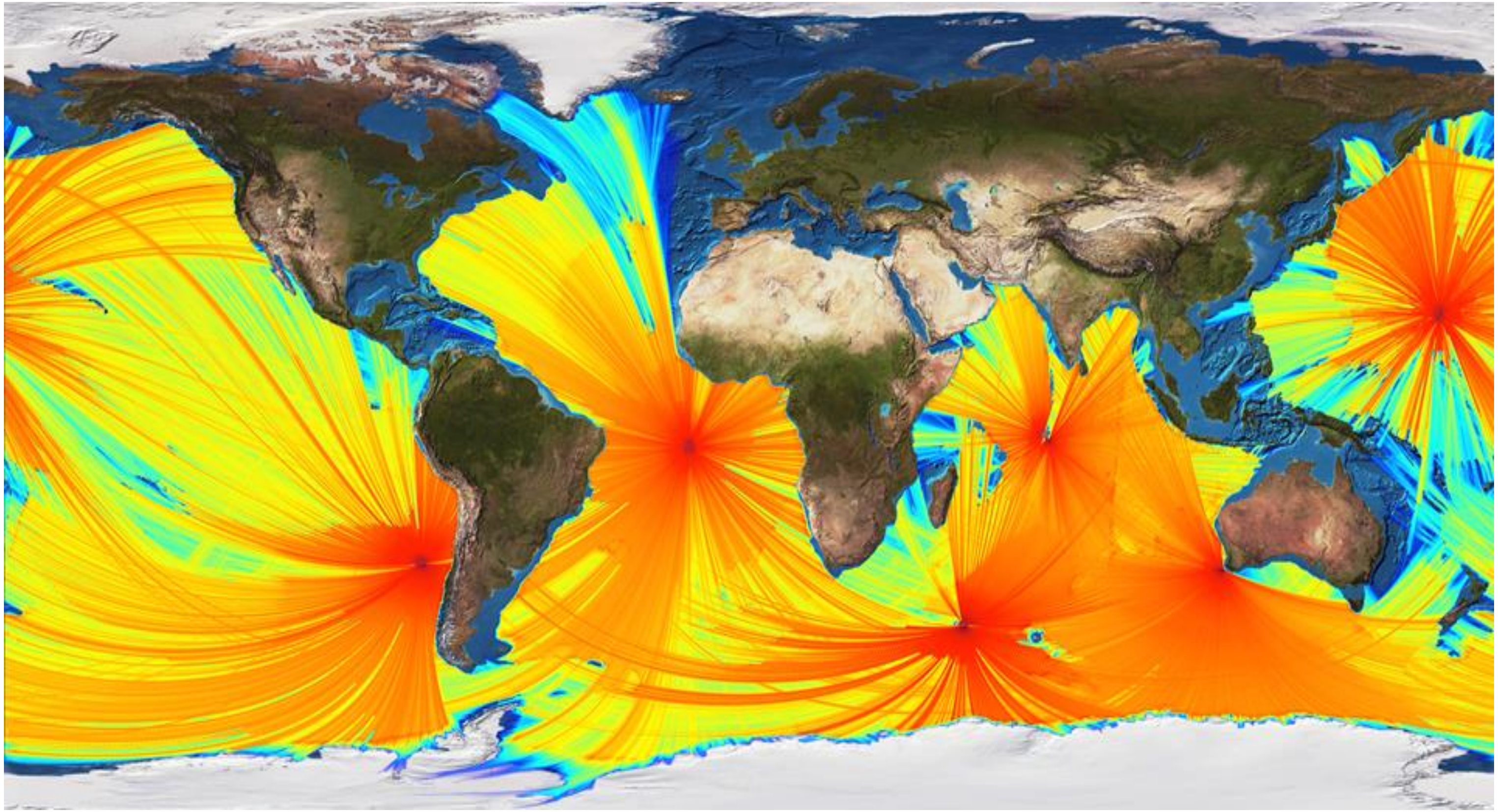
Hydrophone station (up to 100 Hz frequency)



T-phase station (up to 50 Hz frequency)



Detection capability of the HA Hydrophone station network



3-D hydroacoustic model computations courtesy of K.D. Heaney & R.L. Campbell, Applied Ocean Sciences, Inc. (USA)

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HA Hydrophone Station Installation

Installation of HA04 Crozet Islands

@ CTBTO youtube channel:

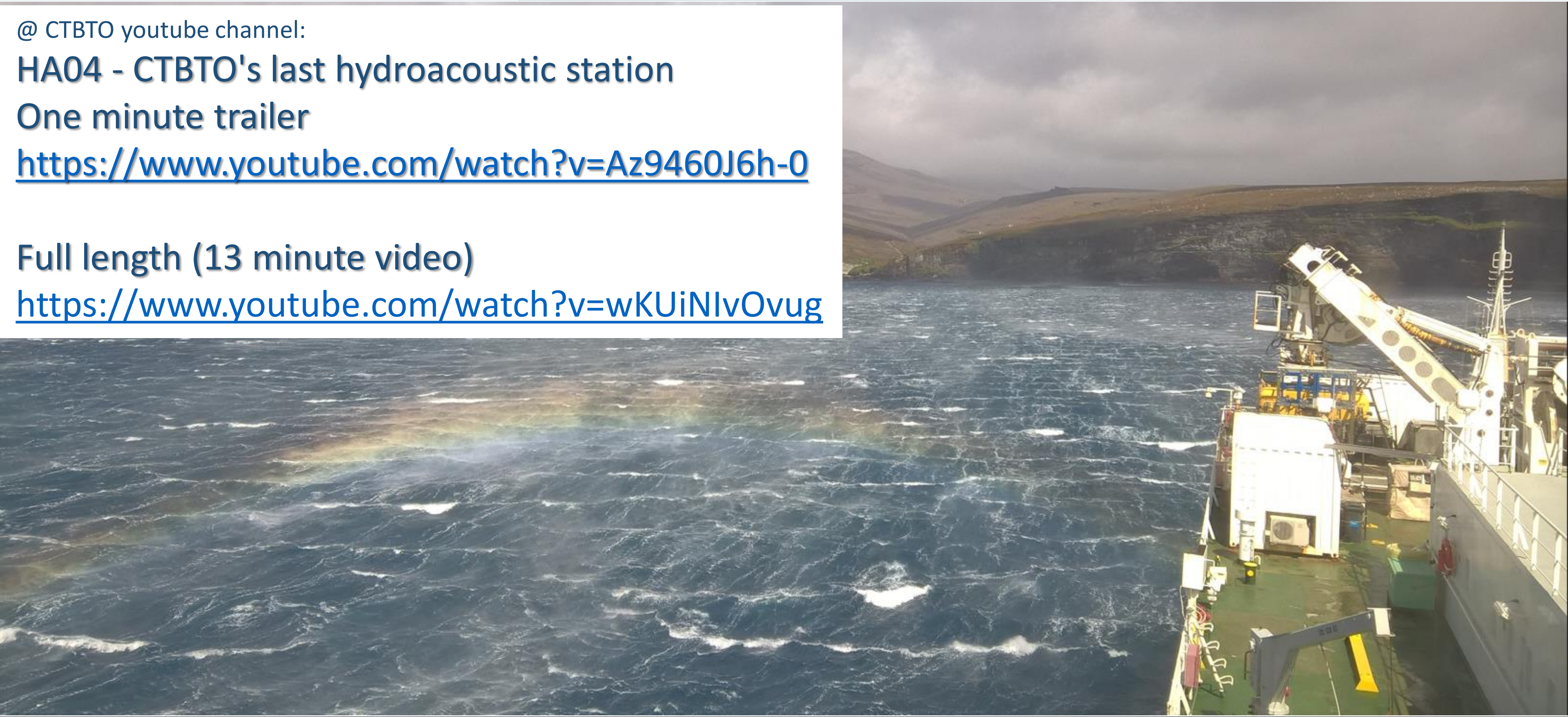
HA04 - CTBTO's last hydroacoustic station

One minute trailer

https://www.youtube.com/watch?v=Az9460J6h-0

Full length (13 minute video)

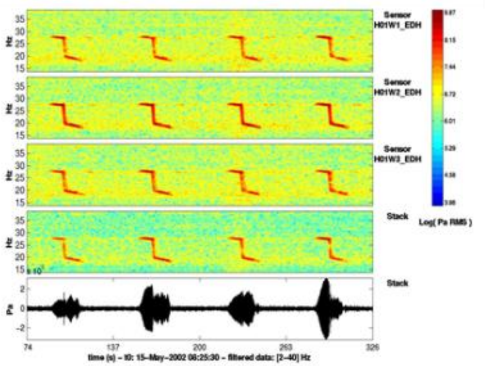
https://www.youtube.com/watch?v=wKUiNIvOvug



Example of Civil & Scientific Applications

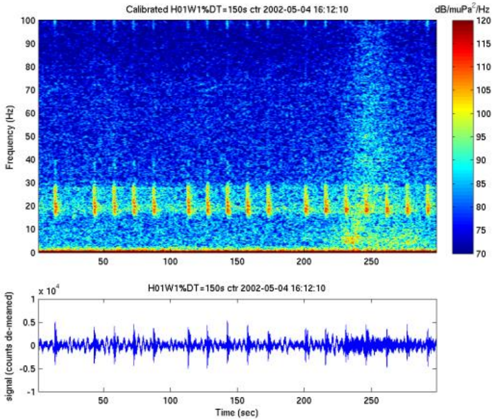
Observing marine mammals – example from HA01 Cape Leeuwin

Blue Whale



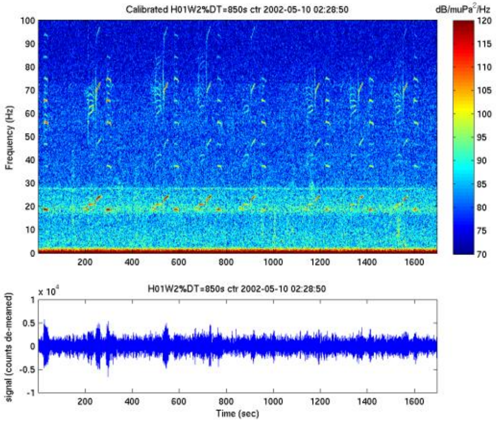
15 May 2002

Fin Whale



4 May 2002

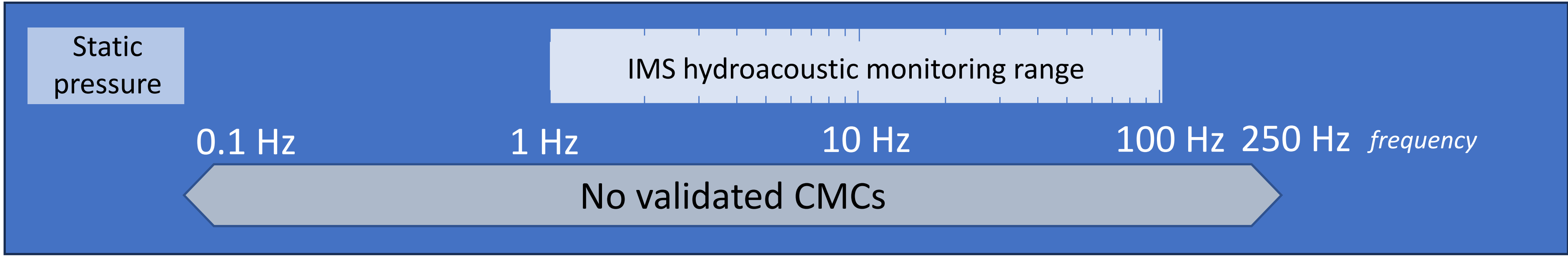
Pygmy Blue Whale



10 May 2002

Sounds played x16 speed

Metrology needs



Infrasound Stations (Arrays)

IMS Infrasound Network

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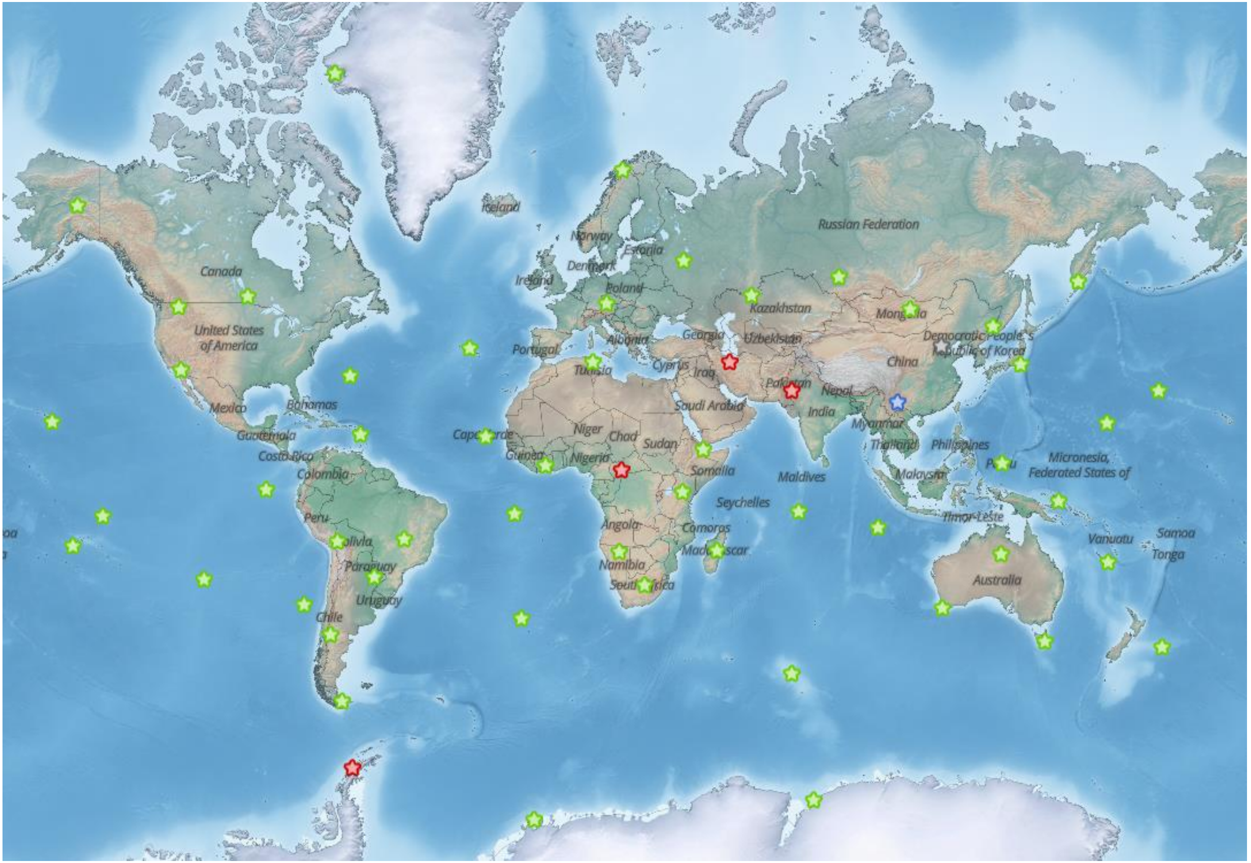
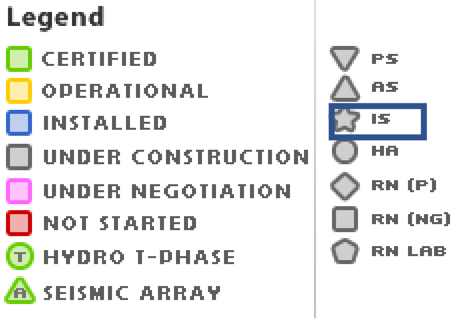
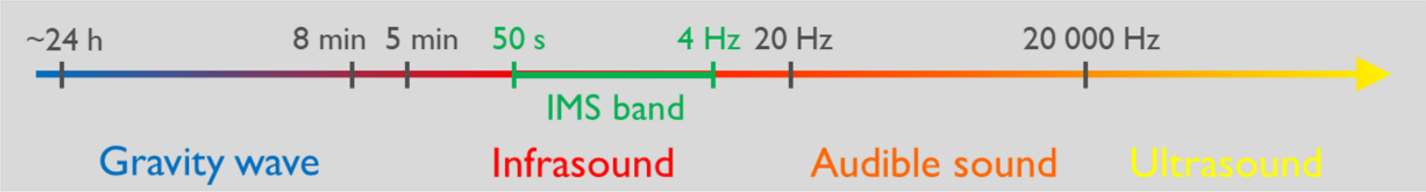
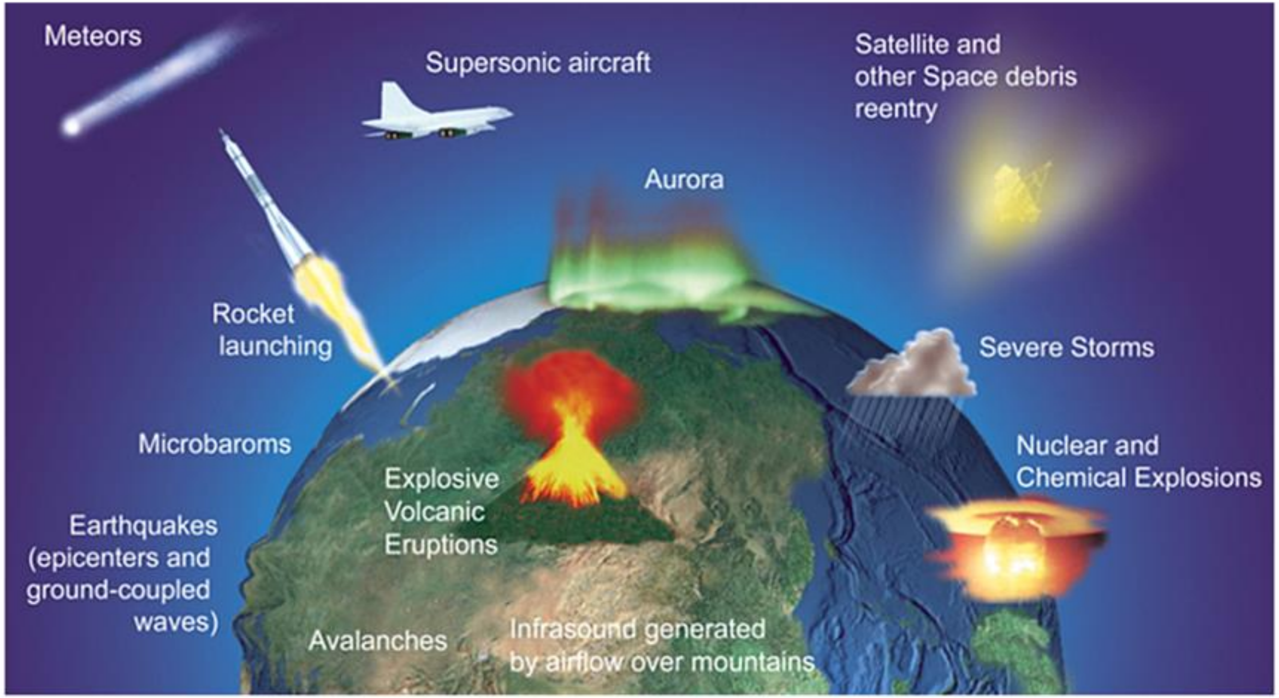


- Infrasound Stations (60)

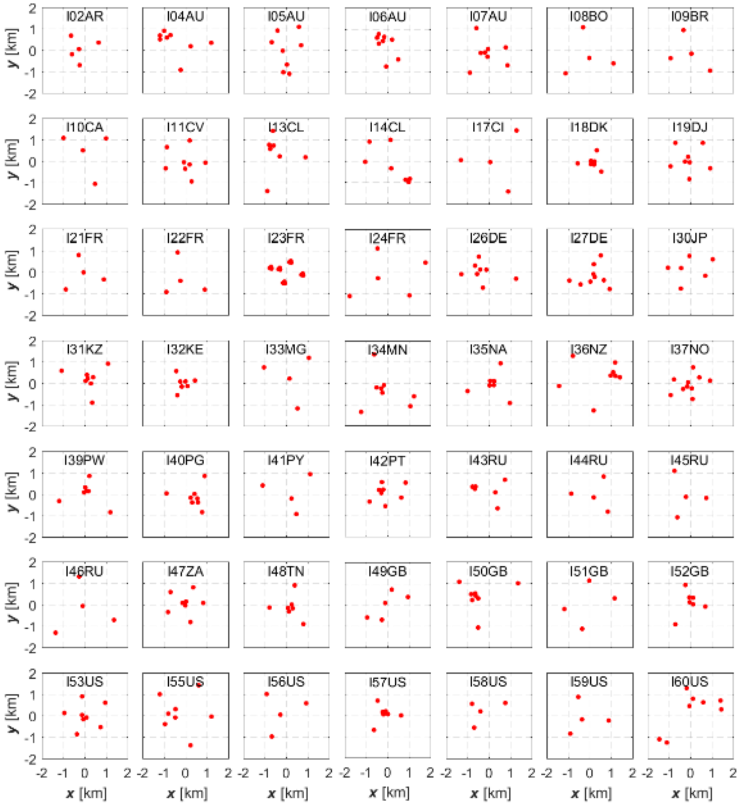


Sources of Infrasound

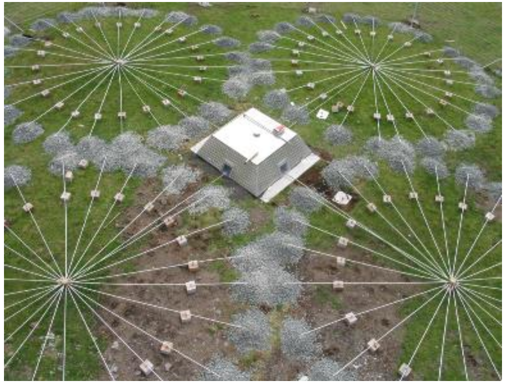




Infrasound arrays

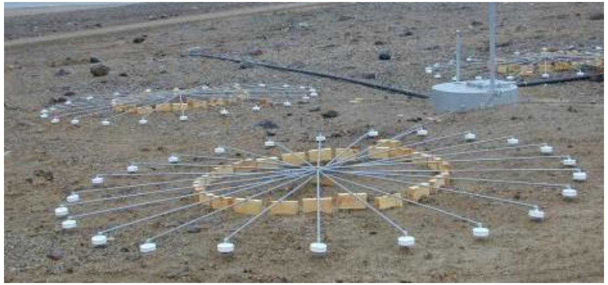


- 4-element array for low-wind conditions
- 8-element array for high-wind conditions
- 1 to 3 km aperture

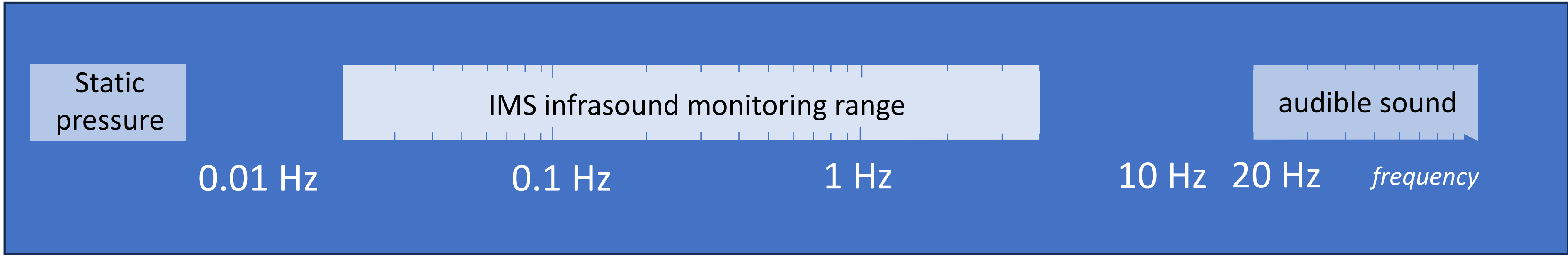


Different environmental conditions






Metrology needs



Radionuclide Stations

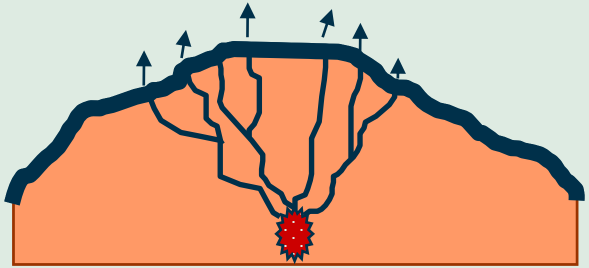
Radionuclide Stations

The radionuclide technology is the only one that is able to confirm whether an explosion detected and located by the others is indicative of a nuclear test.

Particulates and Noble Gas isotopes:

- Above-ground nuclear explosions release both particulates and noble gas isotopes into the atmosphere.
- Underground nuclear explosions can be “sealed off” from the atmosphere, but Noble Gas isotopes can escape through small cracks in the earth.

“Baneberry”, Nevada Test Site 1970.

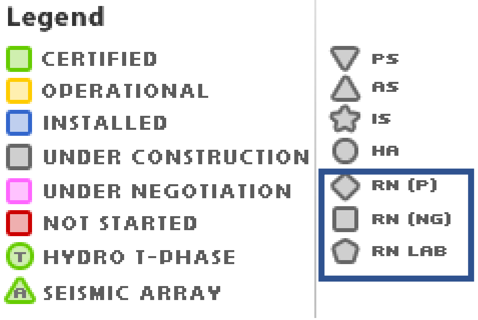


RN design goals

- 90% detection probability within 14 days after a 1 kt nuclear explosion anywhere on the globe
- Radionuclide release from a 1 kT nuclear explosion:
- 10^{15} – 10^{16} Bq release for key nuclides (^{140}Ba, ^{133}Xe)
- Underground nuclear explosion: estimated 0.1 - 1% release
- IMS should detect a release of ~10^{13} Bq anywhere on the globe
- Based on this, the radionuclide station network has been designed:
- 80 particulate radionuclide stations
- of which 40 have noble gas detection capability
- with sensitivity (detection limits) between 10 to 1000 µBq/m3

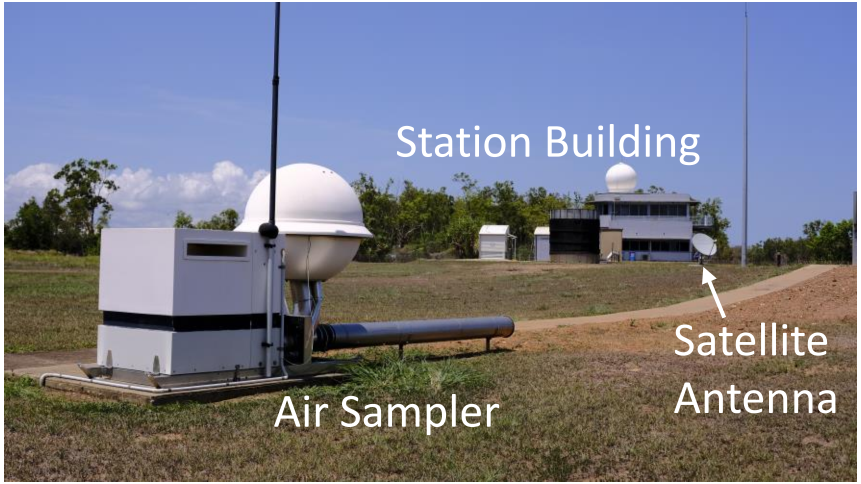
IMS Radionuclide Network

- Radionuclide (RN) Particulate Stations (80)
- RN Stations with additional Noble Gas monitoring (40)
- Radionuclide Laboratories (16)



Radionuclide Station RN 09 Darwin (Australia)

RN Particulate



RN Noble Gas

Particulate Radionuclide Station

General Scheme of RN Monitoring

Data Acquisition

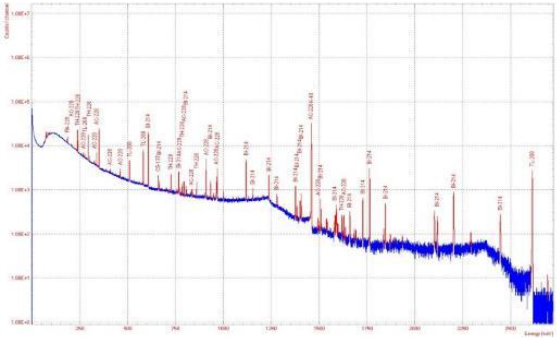
Sampling & Measurement of Aerosol or Noble Gases:

- Filtering for particulate in Aerosol
- Gas collection for Noble Gas

Data Analysis

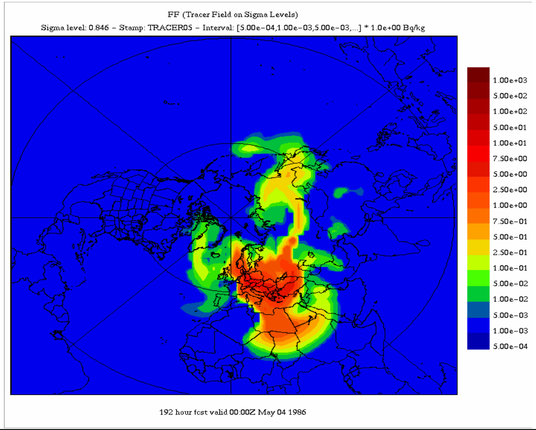
Analysis for presence of fission products

Categorization of measurements (natural, anthropogenic)

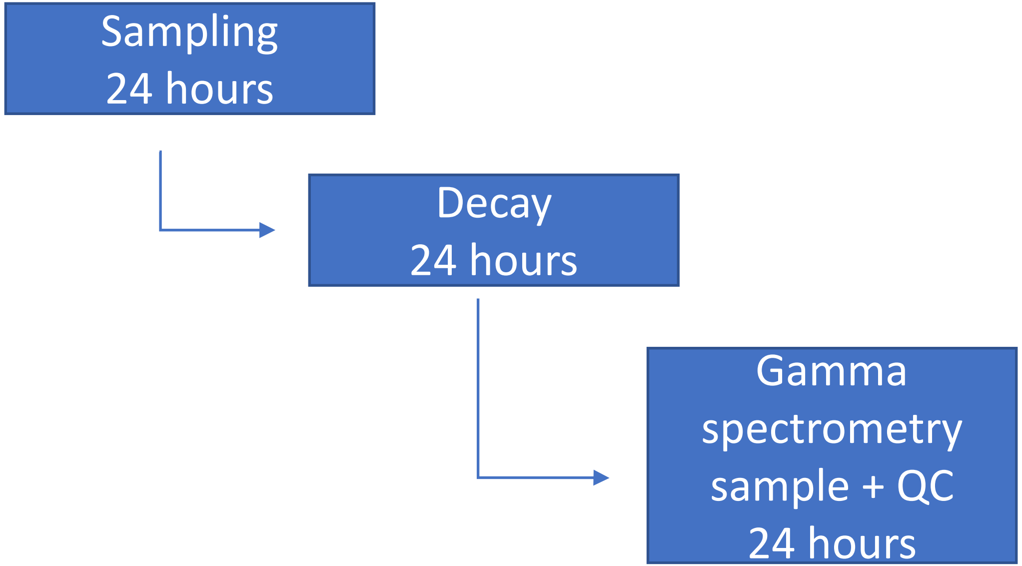


Source location

Inferring source location with **A**tmospheric **T**ransport **M**odels (ATM)



Particulate – time sequence



- Air sampling with > 500m^3/h
- Decay of short-lived natural radioisotopes
- HPGe gamma spectrometry
- Final spectrum sent <72 h hours from start of sampling

For requirements see: CTBT/WGB/TL-11,17/18/Rev.7 *Operational Manual for Radionuclide Monitoring and the International Exchange of radionuclide Data*.

Activity and concentration

$$A\ (Bq) = \frac{N}{T\varepsilon\gamma} K_D$$

$$A\ (Bqm^{-3}) = \frac{N}{T\varepsilon\gamma V\xi} K_D^*$$

γ emission yield: some nuclear data could be improved

V calibrated flow meter

ξ collection efficiency = 1 (0).

ATM backtracking

Concentration – order of magnitude determination of source term

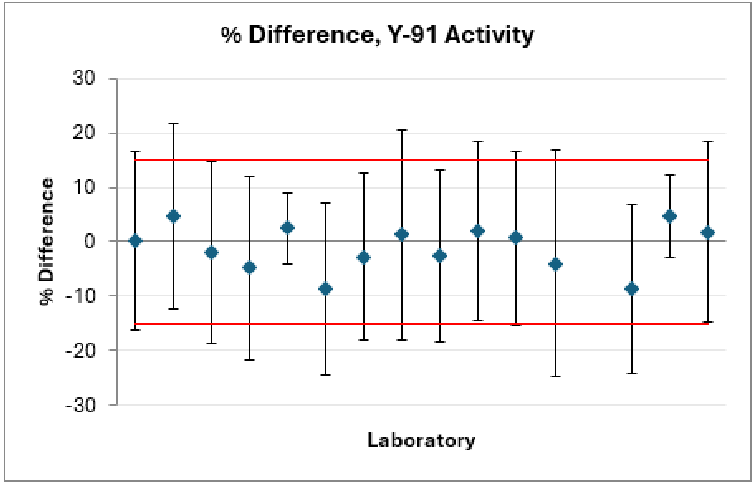
Activity ratios – precise ratios important for classifying event

Aerosol RN Monitoring

Sr-91	9.63	h	Na-24	14.96	h
Y-91	58.51	d	K-42	12.36	h
Y-93	10.18	h	Sc-46	83.79	d
Zr-95	64.02	d	Sc-47	3.349	d
Nb-95	34.98	d	Cr-51	27.7	d
Zr-97	16.91	h	Mn-54	312.1	d
Mo-99	65.94	h	Co-57	271.8	d
Tc-99m	6.01	h	Co-58	70.82	d
Ru-103	39.26	d	Fe-59	44.5	d
Rh-105	35.36	h	Co-60	5.271	y
Ru-106	373.59	d	Zn-65	244.3	d
Ag-111	7.45	d	Zn-69m	13.76	h
Pd-112	21.03	h	Ga-72	14.1	h
Cd-115m	44.6	d	As-74	17.77	d
Cd-115	53.46	h	As-76	1.078	d
Sn-125	9.64	d	Rb-84	32.77	d
Sb-125	2.76	y	Rb-86	18.63	d
Sb-126	12.46	d	Y-88	106.7	d
Sb-127	3.85	d	Zr-89	78.41	h
Sb-128	9.01	h	Rh-102	207	d
Te-129m	33.6	d	Ag-106m	8.28	d
I-130	12.36	h	Ag-108m	418	y
Te-131m	30	h	Ag-110m	249.8	d
I-131	8.02	d	Sb-120	5.76	d
Te-132	3.2	d	Sb-122	2.724	d
I-133	20.8	h	Sb-124	60.2	d
I-135	6.57	h	Cs-132	6.479	d
Cs-136	13.16	d	Ba-133	10.52	y
Cs-137	30.07	y	Cs-134	2.065	y
Ba-140	12.75	d	Eu-152m	9.312	h
La-140	1.678	d	Eu-152	13.54	y
Ce-141	32.5	d	Tm-168	93.1	d
Ce-143	33.04	h	W-187	23.72	h
Ce-144	284.9	d	Ir-190	11.78	d
Nd-147	10.98	d	Ir-192	73.83	d
Pm-149	53.08	h	Au-196	6.183	d
Pm-151	28.4	h	Au-196m	9.7	h
Sm-153	46.27	h	Au-198	2.695	d
Eu-155	4.761	y	Pb-203	51.87	h
Sm-156	9.4	h	Ra-224a	3.66	d
Eu-156	15.19	d	U-237	6.75	d
Eu-157	15.18	h	Np-239	2.357	d

Particulate Radioactivity Monitoring: 92 radionuclides

- Nuclide data



Metrology for Particulate Monitoring

Analyte	Method	calibration
Fission products	High resolution gamma spectrometry	Gamma calibration standard in sample geometry
Activation products	High resolution gamma spectrometry	Gamma calibration standard in sample geometry

Challenges:

- sample inhomogeneities, sample geometry
- Nuclide data

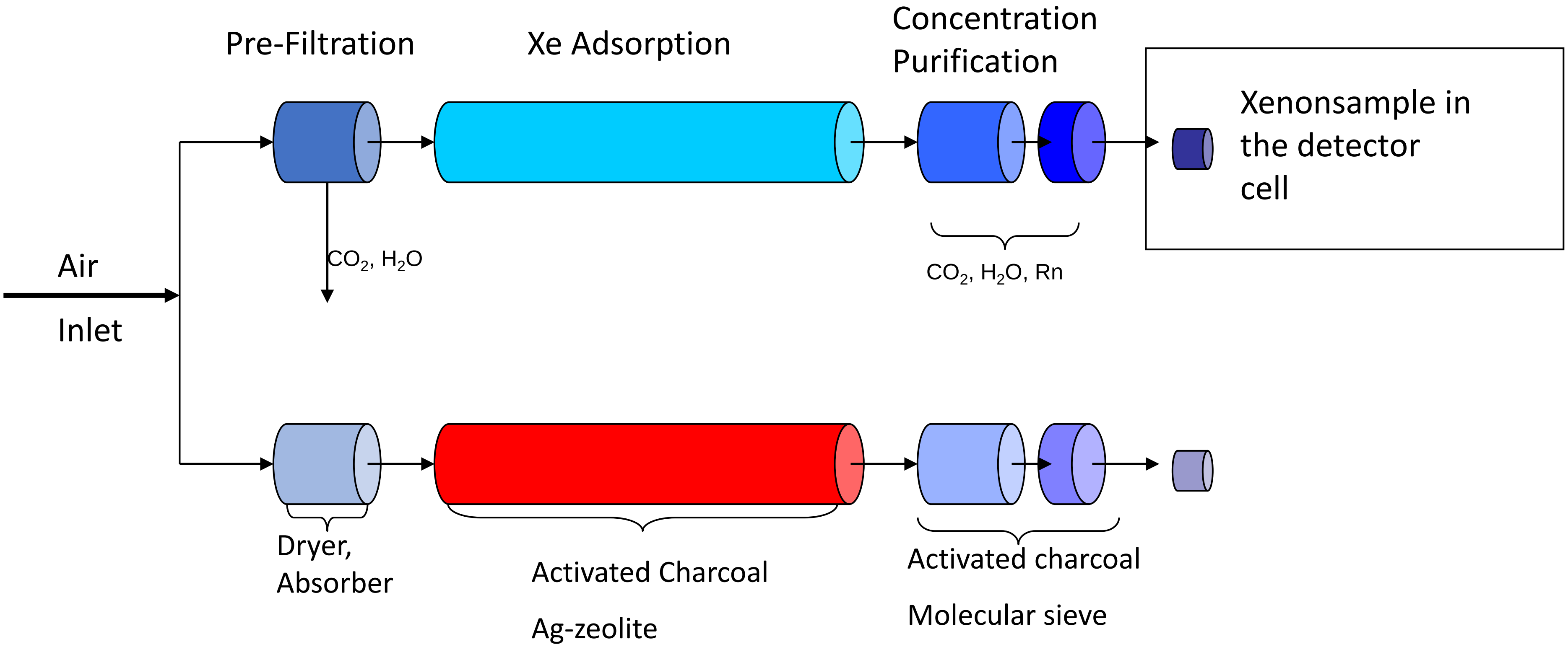
NG monitoring

	Pro	Con
Argon	• High neutron activation yield for ^{37}Ar in Calcium rich rock (^{40}Ca (n,α)^{37}Ar) • Suitable half-life (35 days) • Low atmospheric background	• Difficult to measure at high sensitivity
Krypton		• Moderate fission yield • Long half life (10.8 a) • High atmospheric background (1.5 Bq/m^3)
Xenon	• High fission yields • Suitable half-lives: 9.1 hours to 11.8 days • Low atmospheric background	

NG monitoring

- At least 90% detection capability within 14 days after a nuclear explosion in the atmosphere, underwater or underground for a 1 kT nuclear explosion
- Nuclides of interest:
- ^{131m}Xe (11.9 d)
- ^{133}Xe (5.243 d)
- ^{133m}Xe (2.19 d)
- ^{135}Xe (9.10 h)
- Source Term: range 10^{14} to 10^{15} Bq ^{133}Xe for a 1 kT nuclear explosion
- Minimum detectable concentration of <1 mBq/m3 for ^{133}Xe
- 40 Noble Gas stations

Basic sampling scheme

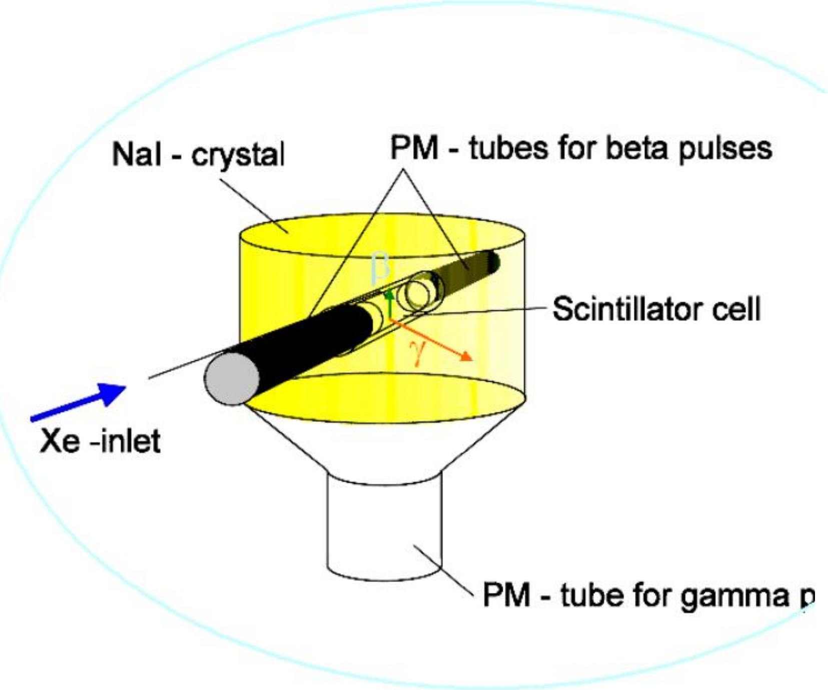


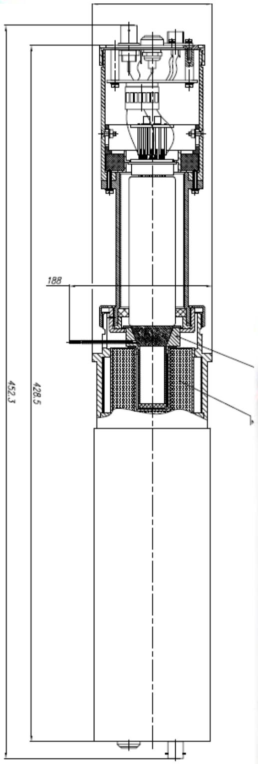
NG systems in-use

Next generation NG systems

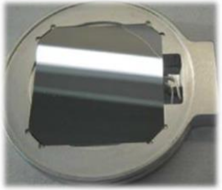
XeInternational

Detection systems

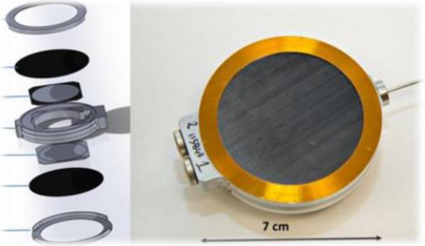




Spectrometer & shield: Open shield view



PIPSBox™



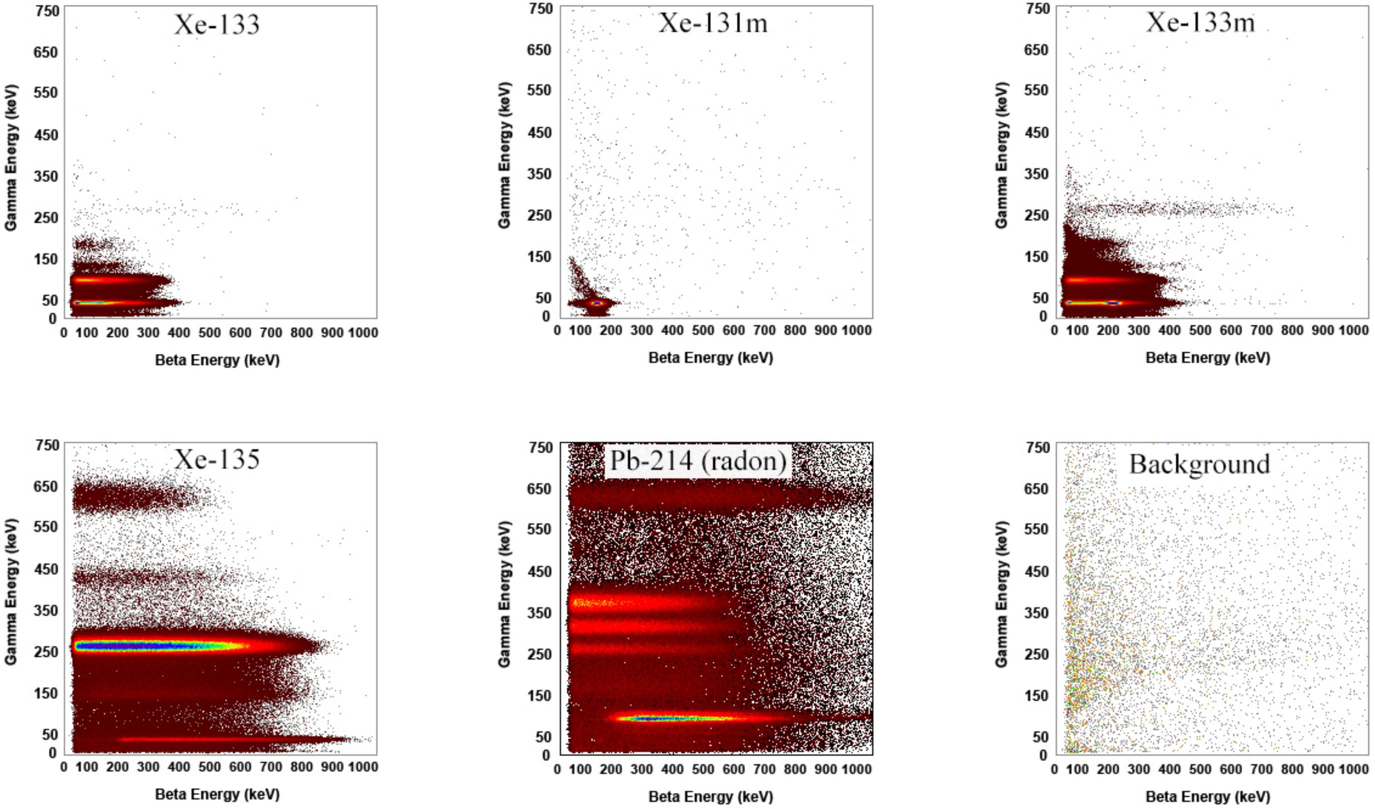
System calibration

- Challenges:
  - Gaseous sources – unknown transfer efficiency
  - Short half-lives

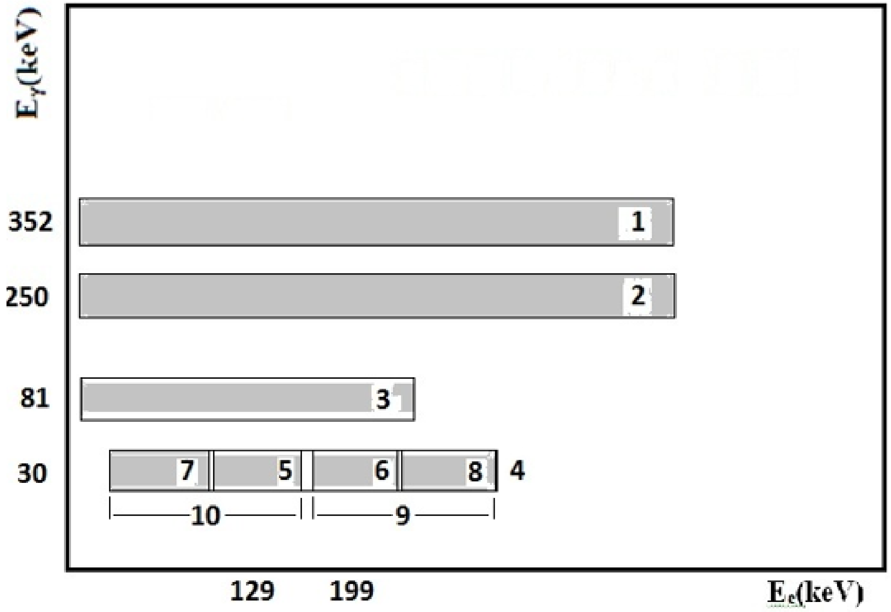
- Gamma spectrometry: standard approach with calibration source

- Beta-gamma coincidence systems:
  - High resolution gamma calibration + xenon spikes
  - absolute calibration

Beta-gamma histogram

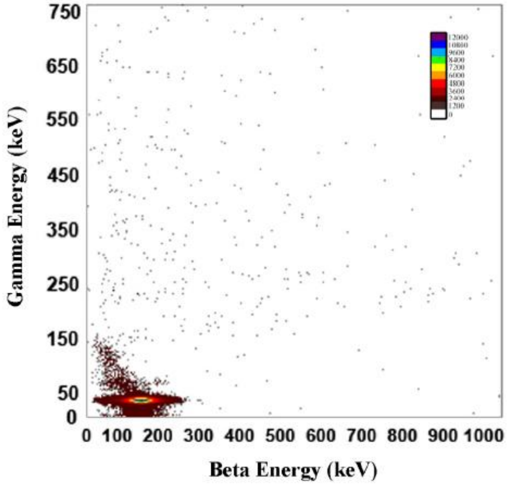


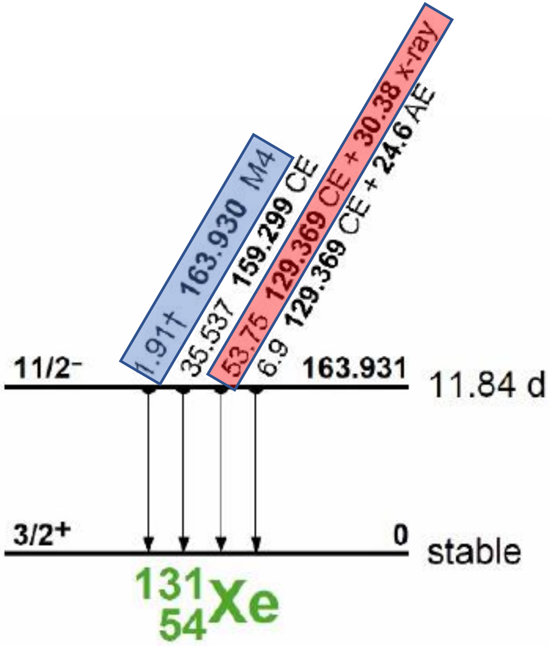
Beta-gamma histogram



Xe isotopes

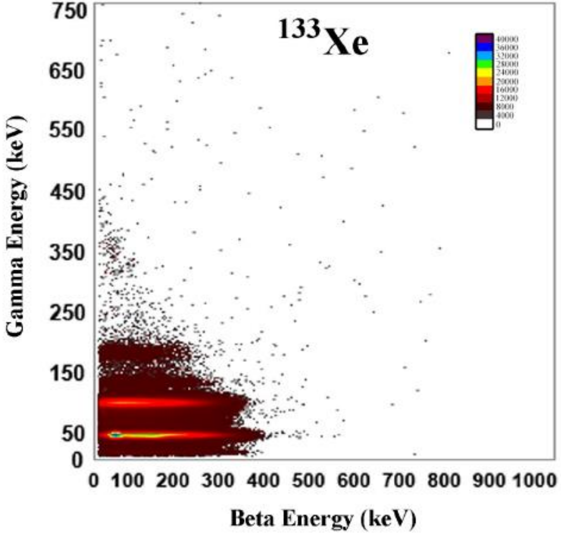
- Xe-131m (11.84 d)
  - γ @ 164 keV (yield 1.9%)
  - CE dominant
  - CE 54% with x-ray

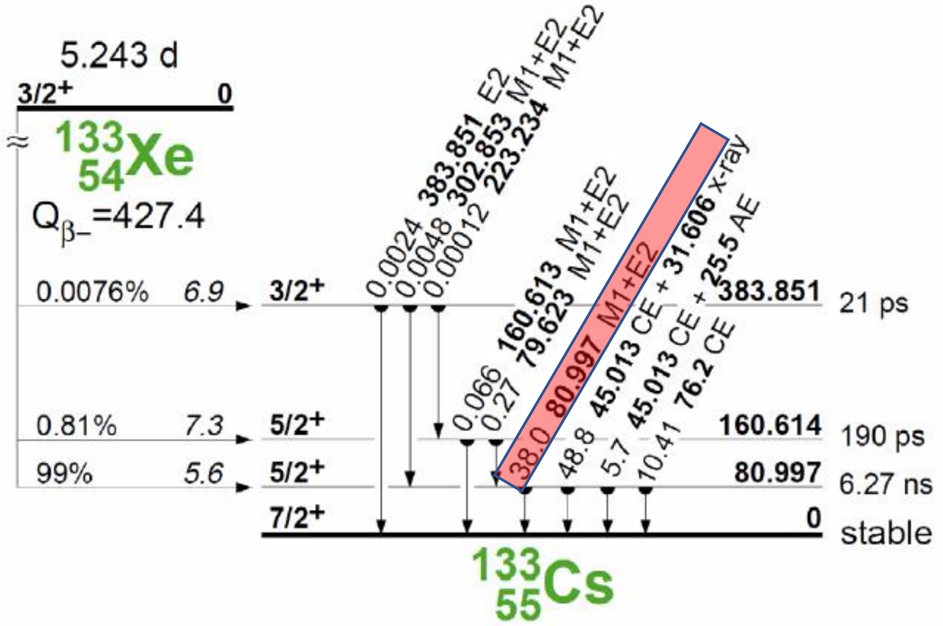




Xe isotopes

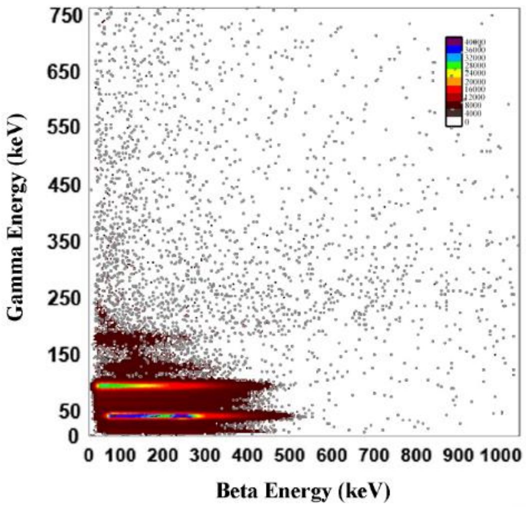
- Xe-133 (5.24d)
  - Dominant decay β 360 keV + 80keV g (37%)

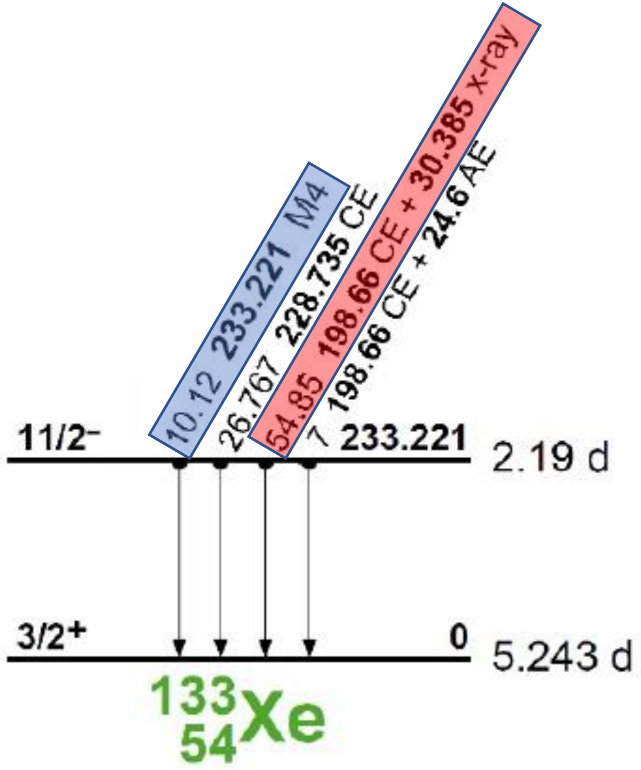




Xe isotopes

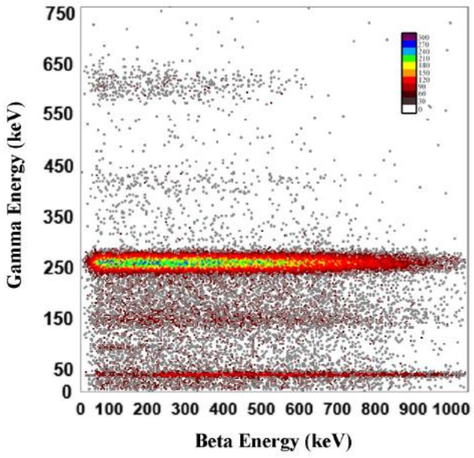
- Xe-133m
- 10 % by gamma 233 keV
- 55% CE + x-ray
- Xe-133 spectrum growing in

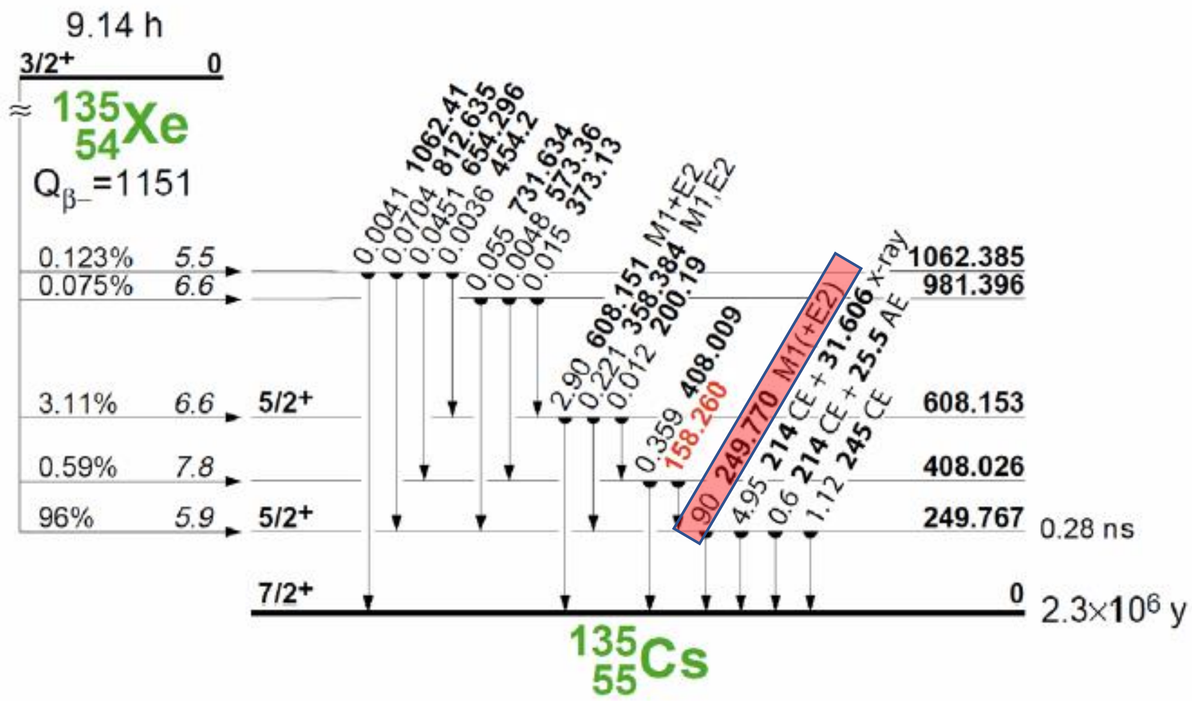




Xe isotopes

- Xe-135
- Beta decay 900keV
  Plus 250keV gamma





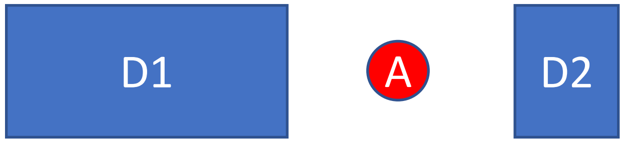
Absolute calibration

$$A = \frac{C_\gamma}{\varepsilon_\gamma BR_\gamma} = \frac{C_\beta}{\varepsilon_\beta BR_\beta} = \frac{C_{\gamma\beta}}{\varepsilon_{\gamma\beta} BR_{\beta\gamma}} \text{ with } \varepsilon_{\gamma\beta} = \varepsilon_\gamma \circ \varepsilon_\beta$$

$$\varepsilon_\gamma = \frac{C_{\gamma\beta}}{C_\beta} \cdot \frac{BR_\beta}{BR_{\beta\gamma}}$$

Simplification

Spatial correlation



NG: Activity and concentration

$$A\ (Bq) = \frac{N}{T\varepsilon\gamma} K_D$$

$$A\ (Bqm^{-3}) = \frac{N}{T\varepsilon\gamma V\xi} K_D^*$$

V not measured (not used)

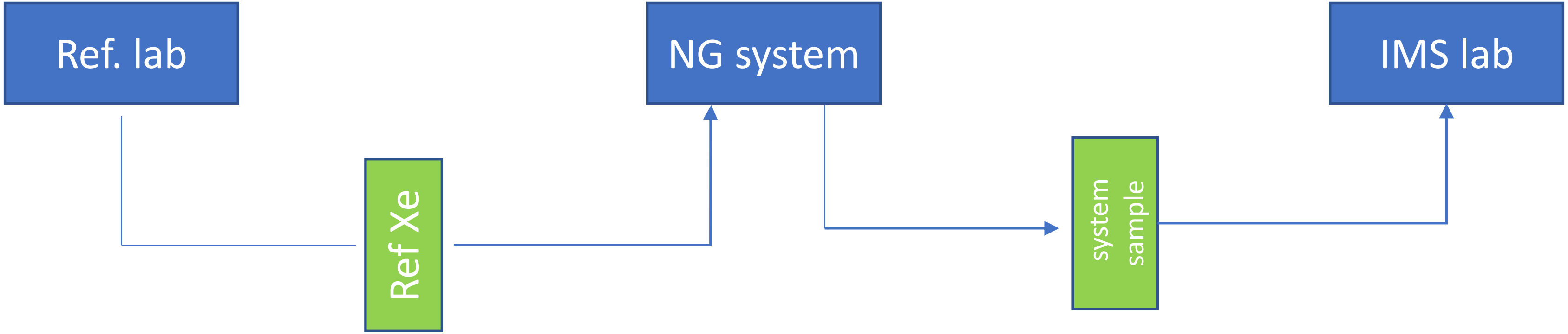
ξ Process efficiency: calculated based on amount of collected xenon and *known* stable xenon concentration in air

$$V\xi = V \cdot \frac{V_{Xe}}{f_{Xe}V} = \frac{V_{Xe}}{f_{Xe}}$$

Volume determination based on single publication

The krypton and xenon contents of atmospheric air
Glueckauf and Pitt
https://doi.org/10.1098/rspa.1956.0057

Spike QC programme

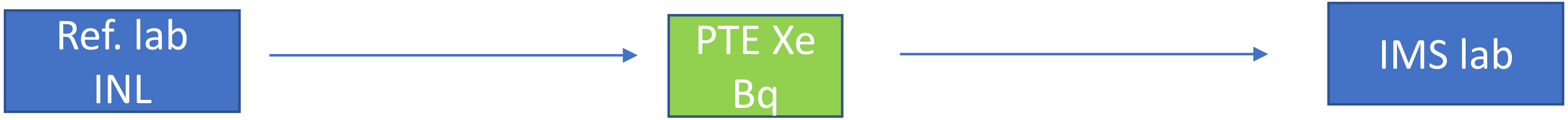


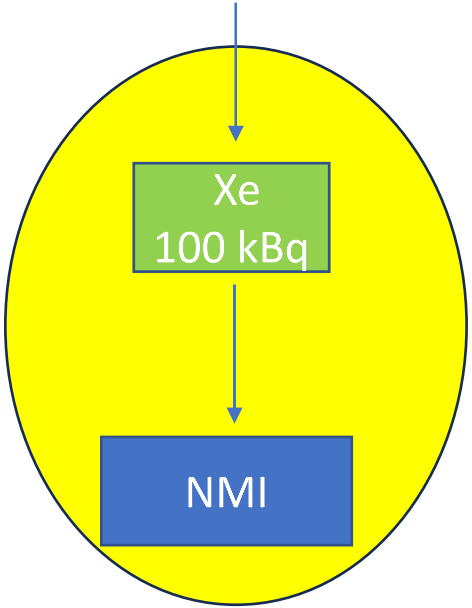
Ref Xe sample:
2 (131m, 133),
3 (133, 133m, 135)
Or
4 (131m, 133,133m, 135)
Certified activities => ratios

System:
Activity concentration
Xe volume

IMS laboratory result:
(Xe-133, Xe-131m)
Activity concentration
Xe volume

Lab Proficiency Testing





No reference material for xenon

Proficiency Test exercise for IMS Laboratories (6 + 3)
Atmospheric samples (mBq)
PTE samples (Bq)

Planned:
INL “comparison” with NMI

Metrology for Noble Gas Monitoring

Analyte	Method	calibration
Xenon isotopes	High resolution gamma spectrometry (low sensitivity, interferences)	Gamma calibration standard in sample geometry
Xenon isotopes	Beta-gamma coincidence spectrometry	Absolute calibration

Challenges:

- Traceability through gamma spectrometry only
- Limited number of laboratories with xenon measurement capability
- Environmental measurements at mBq level

Summary

Metrology for radionuclide monitoring:

Gamma emitting nuclides: calibration – ok.

- Nuclide data – data for some isotopes could be improved

Xe (Xe-131m, Xe-133, Xe-133m, Xe-135) no primary standard

Traceability through gamma spectrometry only

- New determination of stable xenon in air (nice-to-have)
- develop (revive) gas measurement capability at NMIs

Thank you!