GLY 6739.017S26: Computational Seismology

Notebook 05: History of Seismic Instrumentation

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Seismic monitoring is often taught as a combination of **sensors**, **signals**, and **algorithms**. In practice, however, seismic monitoring systems are best understood as **end-to-end computational systems**, in which instrumentation, recording media, telemetry, digitization, storage, visualization, and processing are tightly coupled.

This notebook traces the evolution of seismic instrumentation from **analog mechanical systems** to **modern digital networks**, emphasizing **why each technological transition occurred**, **what limitations it solved**, and **what new computational constraints it introduced**. In particular, we highlight how changes in **recording media**—from photographic film, to paper, to digital samples—directly shaped what could be detected, displayed, shared, and automated.

This historical perspective provides the foundation for understanding **digitizers, analog-to-digital conversion (ADC), sampling, quantization, telemetry bandwidth, and real-time processing**, which we will explore next in class and lab.

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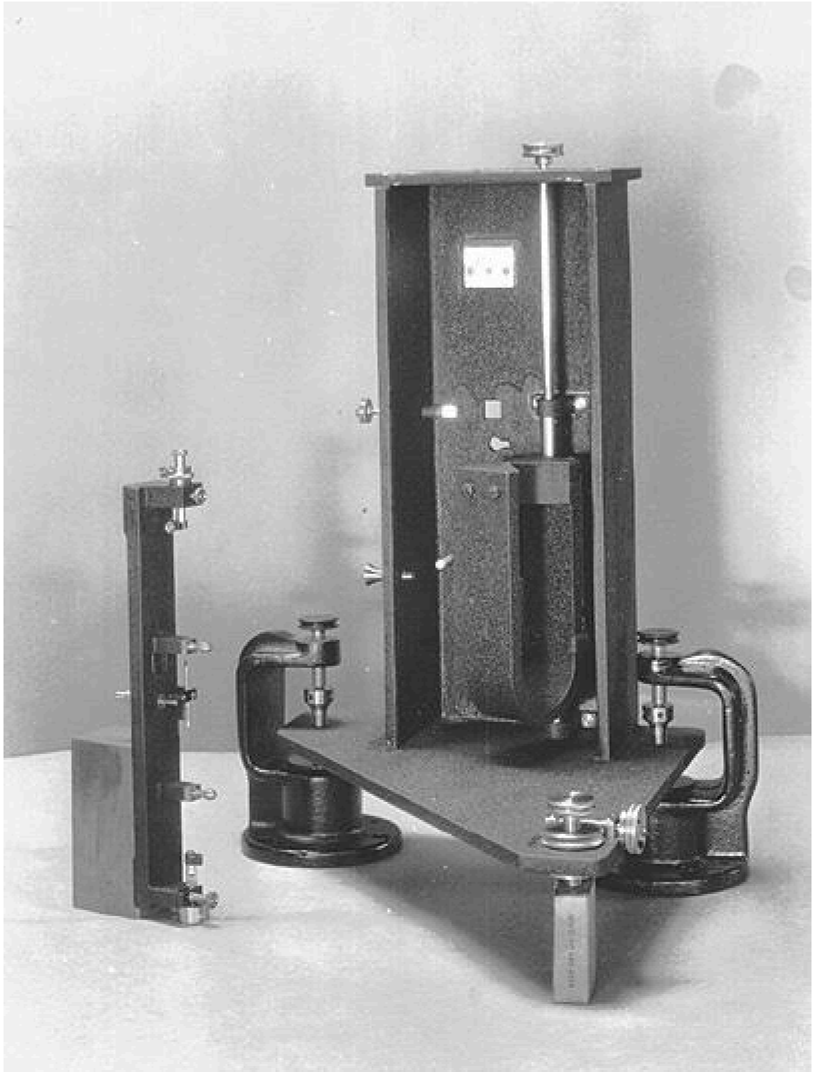
1. Analog Seismology: Mechanical Sensors and Physical Records

From the late 19th century through much of the 20th century, seismic monitoring relied entirely on **analog mechanical seismographs**. These instruments used suspended masses whose relative motion was converted into a visible trace.



Wood-Anderson seismograph

Two distinct recording technologies dominated this era.

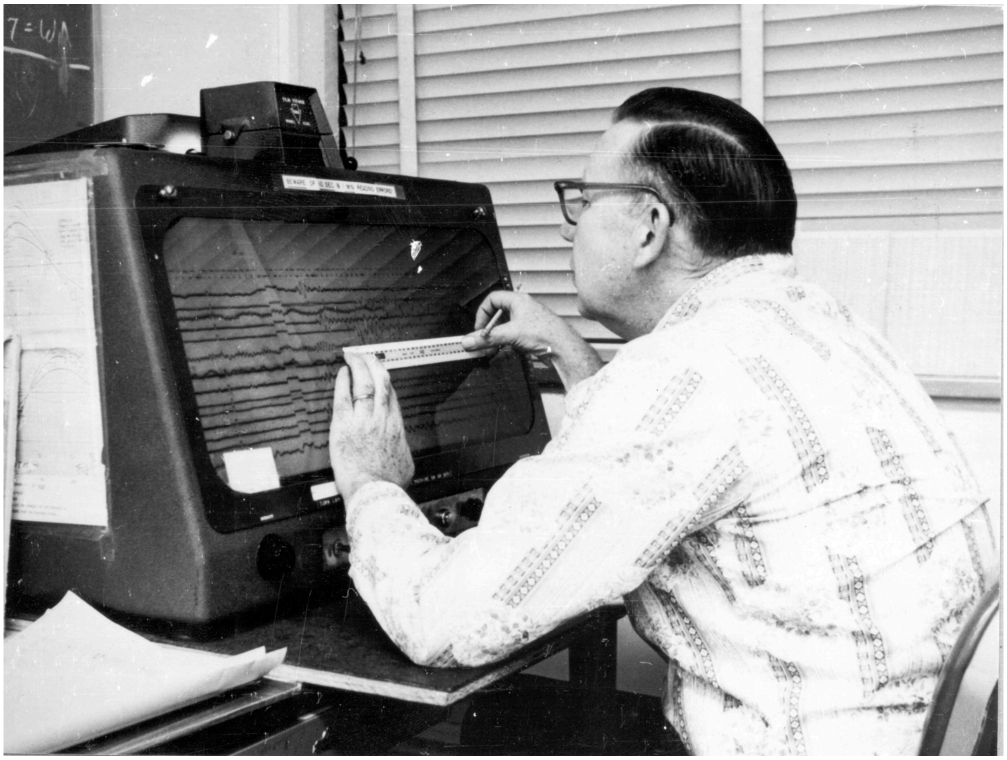
1.1 Photographic Seismogram Recording (Late 1800s–Mid 1900s)

The **earliest continuous seismic records were photographic**. A mirror or light beam attached to the seismometer mass exposed **photosensitive paper or film** wrapped around a rotating drum.

Photographic recording was adopted first because it:

- Introduced **negligible mechanical loading** on the pendulum
- Allowed **very high sensitivity**, especially at long periods
- Was essential for detecting **teleseismic earthquakes**

Photographic seismograms underpinned early global seismology and later became the standard recording method for global research networks.



Develocorder analysis

However, photographic systems:

- Required **chemical development** (because of this, they were called "develocorders")
- Could not be inspected in real time
- Were labor-intensive to archive, duplicate, and distribute

These limitations became increasingly problematic as observatories shifted from purely scientific observation toward **operational monitoring**.

1.2 Paper-Based Recording: Smoked Paper and Ink Helical Drums (Early–Mid 1900s)

As seismic networks expanded—especially for **local and regional earthquakes**—many observatories adopted **paper-based continuous recording**, including:

- **Smoked paper drums**, where a stylus scratched soot
- **Ink-on-paper helicorders**, producing continuous helical traces

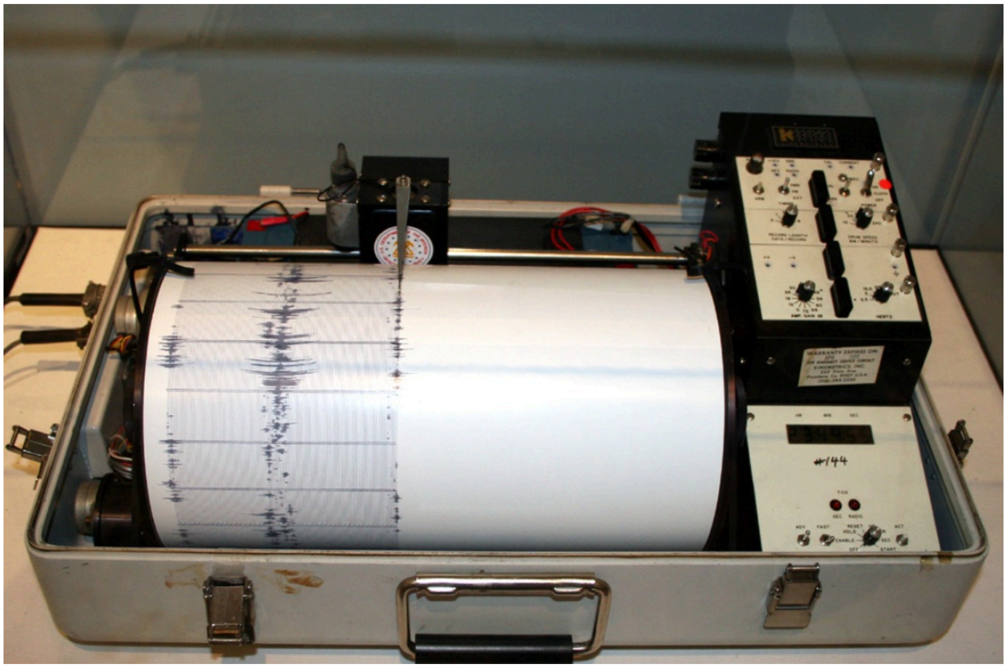
By the mid-20th century, routine monitoring relied heavily on **short-period electromagnetic seismometers** paired with paper drum recorders.

Paper systems were favored because they:

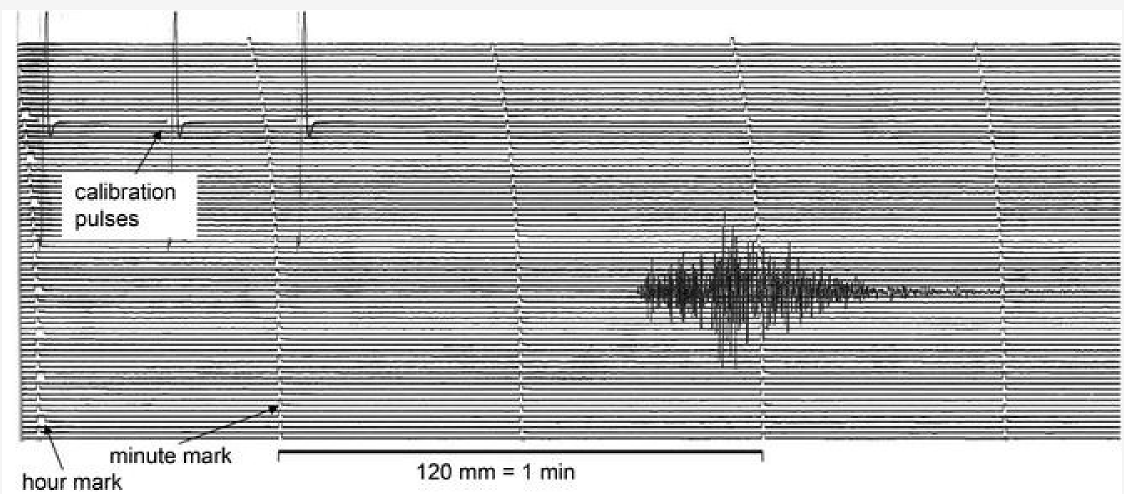
- Provided **immediate visual feedback**
- Supported **real-time operational decision-making**
- Were cheaper and easier to maintain than photographic systems

Their drawbacks included:

- Limited dynamic range
- Stylus skipping or saturation during strong motion
- Mechanical wear and frequent maintenance



Helical drum recorder



Helical drum plot

Key characteristics of analog seismic systems

- **Continuous recording**, but only on **film or paper**
- **Dynamic range limited** by optics, ink flow, paper width, or film exposure
- **Instrument response fixed** by mechanical and electromagnetic design
- **Analysis performed visually** by trained analysts
- Arrival times and amplitudes measured **manually**

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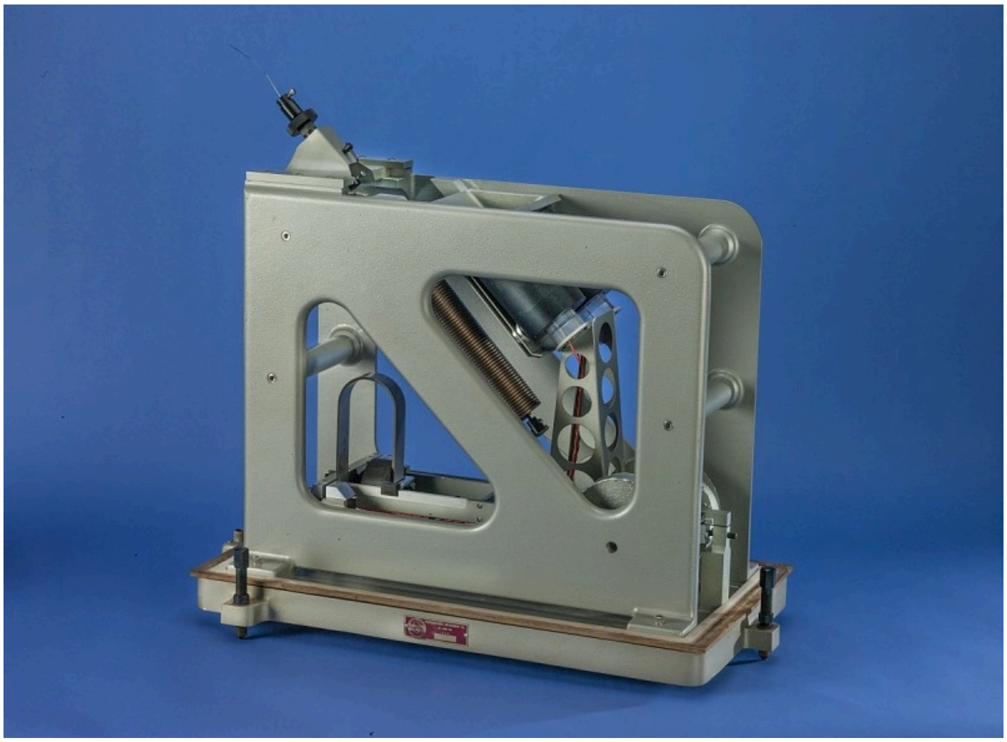
2. Global Standardization: WWSSN and the Plate Tectonics Revolution

After World War II, the need to detect and locate underground nuclear tests motivated the creation of the **World-Wide Standardized Seismograph Network (WWSSN)** in the early 1960s.

WWSSN deployed **identically calibrated short-period and long-period analog seismographs** worldwide, recorded primarily on **standardized photographic media**.



Press-Ewing Vertical Seismometer. These were paired with develocorders
Why this mattered:

- For the first time, seismic data were **globally comparable**
- Uniform instrumentation enabled consistent magnitude and location estimates
- Global earthquake catalogs revealed coherent seismicity patterns

These observations provided decisive evidence for **plate tectonics** in the late 1960s–1970s.

Computational implication: Standardized instrumentation made **global computation meaningful**, even though processing was still batch-based and waveform data remained analog.

Why Photographic Recording Was Phased Out

Photographic recording was not abandoned because it lacked quality, but because it **could not scale operationally**.

Once it became possible to:

- **Digitize continuously**
- **Store long time series electronically**
- **Transmit data in real time**

photographic systems offered no advantage. Continuous digital data streams made it possible to implement **automated detection algorithms**, most notably **STA/LTA detectors**, which require continuous numerical time series and cannot operate on film.

This marks the moment when **computation moved from the analyst to the system**.

Why Paper Records Persisted Longer

Paper records persisted well into the digital era because they solved a different problem: **real-time situational awareness**.

Helicorders allowed:

- Operators to glance at current activity
- Rapid assessment during crises
- No dependence on computers or networks

At many observatories, paper and digital systems ran **in parallel** for years.

Paper was finally phased out when software systems—such as **USGS SWARM** and similar waveform visualization tools—made it easy to:

- Display continuous data on screens
- Rescale amplitudes instantly
- Zoom and scroll in time
- View spectrograms and multi-station data
- Eliminate consumables (paper, ink, styluses)

At that point, computers became **better helicorders than helicorders**.

3. Broadband Sensors: Dynamic Range Forces Digitization

The next major instrumentation revolution occurred in the **late 1980s** with the development of **portable broadband seismometers**.

Guralp CMG-3 seismometer"

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Strekheisen STS-2

No description has been provided for this image
Nanometrics Trillium Compact

Unlike classical short-period instruments, broadband sensors use **force-balance (feedback) designs**, allowing them to record:

- Earth tides and free oscillations
- Local and teleseismic earthquakes
- Across several orders of magnitude in amplitude and frequency

Why this forced change:

- The dynamic range exceeded what analog telemetry could transmit
- Analog links would clip exactly the signals broadband sensors were designed to preserve

Result: Broadband sensors *required* **digitization at or near the sensor**, marking the true beginning of **modern digital seismology**.

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4. Digitizers Become Computers (2000s)

By the 2000s, seismic digitizers evolved from simple ADC boxes into **networked embedded computers**, incorporating:

- High-resolution ADCs
- Embedded CPUs
- GPS timing
- Ethernet/IP networking
- Local buffering and storage

Key transition: Digitizers became **IP-addressable devices**, not peripherals.

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Nanometrics Centaur Digitizer

Kinemetrics Q330 Digitizer

Computational implication:

- End-to-end digital networks
- Remote configuration and health monitoring
- Real-time streaming into processing pipelines
- Tight coupling between instrumentation and software

This is where **sampling rate, bit depth, quantization noise, and telemetry bandwidth** become first-order design constraints.

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5. Large-N Instrumentation

5.1 Nodal Seismometers

The **2010s** saw the rise of **large-N seismic instrumentation**, enabled by miniaturization, low-power electronics, and flash storage.

Nodal seismometers are:

- Small, self-contained
- Battery powered
- Deployed by the hundreds to tens of thousands
- Retrieved after recording (often no telemetry)

Nodal short-period seismometer

5.2. Distributed Acoustic Sensing (DAS)

In parallel, **Distributed Acoustic Sensing (DAS)** repurposed **fiber-optic cables** as dense linear seismic arrays.

DAS enables:

- Meter-scale spatial sampling
- Tens of thousands of “channels”
- Urban, subsea, and infrastructure-based sensing

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DAS
Across nodal arrays, and DAS:

- Spatial sampling exploded

- Wavefield imaging improved dramatically
- Data rates dwarf traditional seismology
- Data volume became enormous
- Human inspection is impossible at scale
- Automation becomes mandatory
- Instrumentation and computation are inseparable

And for real-time DAS, real-time processing requires GPUs and streaming architectures

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6. Citizen and Educational Seismology

Alongside professional networks, **low-cost digital seismology** expanded rapidly.

A major milestone was the **Raspberry Shake** (introduced 2016), which integrates:

- A sensor
- Digitizer
- Linux computer
- Internet telemetry

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Raspberry Shake
Why this matters:

- Public engagement
- Dense informal networks
- Education and outreach
- Democratization of seismic data

Computational implication: Instrumentation now assumes **cloud connectivity and real-time processing** by default.

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7. Big Picture: Instrumentation Drives Computation

Across more than a century of seismic monitoring, a consistent pattern emerges:

Instrument advance	New computational requirement
Photographic drums	Manual global interpretation
Paper helicorders	Real-time human monitoring
Digital telemetry	Automated detection (STA/LTA)

Instrument advance	New computational requirement
Broadband sensors	High-dynamic-range ADCs
Networked digitizers	Real-time processing
Nodal & DAS arrays	Scalable automation
Citizen sensors	Cloud infrastructure

Each instrumentation revolution **forces a corresponding computational revolution**.

Looking Forward to Lab

In the next class and lab, we focus on **the digitizer as the boundary between the physical and digital worlds**, including:

- ADCs
- Sampling and aliasing
- Quantization and bit depth
- Dynamic range
- Telemetry and buffering

Understanding digitizers is not about memorizing specifications—it is about understanding **why modern seismic systems look the way they do**.