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Workshop Science In Colonial India: Instrument Fabrication At Bose'S And Raman'S Laboratories (1900–1930) And Lessons For Indigenous Precision Manufacturing

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Abstract- Histories of science in colonial India usually celebrate discoveries and the people who made them. This paper looks instead at the instruments. It examines how Jagadis Chandra Bose at Presidency College and the Bose Institute, and C. V. Raman at the Indian Association for the Cultivation of Science, Calcutta, designed, built and adapted the apparatus on which their research depended between about 1895 and 1930. Drawing on published descriptions of their apparatus, the paper reconstructs three cases: Bose's millimetre-wave optics, Raman's mechanical studies of bowed strings, and the light-scattering experiments that led to the Raman effect in 1928. For each case it identifies the quantity that limited the experiment and estimates, from elementary physics, the precision the apparatus had to achieve. Bose's grating measurements required angular settings of a fraction of a degree; Raman's bowing apparatus had to hold the bow force within a window that narrows sharply as the bow approaches the bridge; and the 1928 experiments needed modest spectral resolution, of order 10^3, but very high light-gathering power. The analysis shows a consistent design philosophy: identify the dominant constraint, meet it with simple and locally made means, and avoid spending precision where it is not needed. The paper argues that this philosophy, together with the in-house workshop as an institution, offers lessons for indigenous precision manufacturing today.

Keywords: J. C. Bose; C. V. Raman; scientific instruments; workshop science; colonial India; Raman effect; precision engineering; indigenous manufacturing

I. INTRODUCTION

Experimental science depends on instruments, and instruments depend on the people and workshops that make them. In Europe in the late nineteenth and early twentieth centuries, physicists could draw on a large industry of instrument makers. In colonial India that industry was thin. Precision instruments were largely imported, often at great cost and after long delays, and the colonial scientific services were organised around survey, meteorology and other practical needs of government rather than around research laboratories [1], [2]. Indian physicists who wished to do original experimental work therefore had to design and build much of their own apparatus.

The two most successful Indian experimental physicists of the period, Jagadis Chandra Bose (1858–1937) and Chandrasekhara Venkata Raman (1888–1970), both did so. Bose's millimetre-wave research of the 1890s was carried out with radiators, horns, lenses, polarisers, gratings and detectors that he built himself in Calcutta [3], [4]. Raman's research at the Indian Association for the Cultivation of Science (IACS) began with acoustical experiments on improvised apparatus and culminated in the discovery of the Raman effect with equipment that was, by international standards, modest [5]–[7]. The early phase of modern physics in India from 1900 to 1930, which these careers span, has been analysed in a Kannada-language doctoral study [8].

This paper asks what can be learned from their instruments. It does not attempt a complete inventory, which the surviving sources do not allow. Instead it reconstructs three cases from published descriptions and asks, for each, what precision the experiment actually required. The aim is to identify a design

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philosophy and to consider what it implies for the development of precision manufacturing in India today. Fig. 1 places the main events on a timeline.

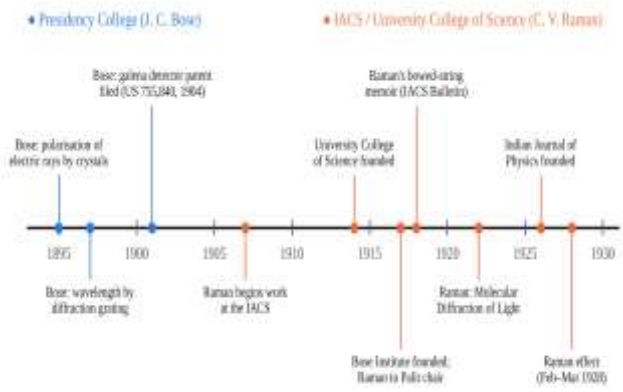


Fig. 1. Timeline of selected events in instrument-based research by J. C. Bose and C. V. Raman in Calcutta, 1895–1928.

II. THE SETTING: INSTRUMENTS IN A COLONIAL ECONOMY

The colonial state did maintain instrument workshops. The Survey of India and the meteorological department, for example, needed theodolites, chronometers and barometers, which they repaired, calibrated and in some cases made [1]. These workshops served practical administration. Their skills were rarely available to college laboratories, whose budgets for apparatus were small and whose purchases were usually made from catalogues of British and German firms [2].

Historians have emphasised that knowledge in colonial India was produced through exchanges in which local skills, including the skills of craftsmen, were indispensable, even when they went unrecorded [9]. Laboratory instruments are a good example. Bose and Raman designed their apparatus, but the cutting, turning, soldering and polishing were done by workmen whose names are seldom preserved. Any account of their instruments is therefore also an account of a hidden workforce, and of the conditions under which precision could be achieved without an established instrument industry. Studying how Bose and Raman worked within these constraints is therefore also a way of studying the material basis of colonial science, a subject that has received less attention than its intellectual and institutional history.

III. CASE ONE: BOSE'S MILLIMETRE-WAVE OPTICS

1. The Apparatus

In 1894 Bose converted a small room adjoining a bathroom at Presidency College into a laboratory [3]. Over the following years he built a complete set of apparatus for the quasi-optical study of electric waves (Fig. 2). Oscillations were produced by sparks between two hollow metal hemispheres, partly inside a metal enclosure that acted as an overmoded circular waveguide, and the radiation left through an aperture. To collect radiation at the receiver he used what he called a "collecting funnel", in effect a pyramidal horn antenna. He made lenses of glass and of sulphur to collimate the beam, dielectric prisms to refract it, and a polariser formed from a book with sheets of tinfoil interleaved between its pages. He also made a reflecting diffraction grating from metal strips and used it to measure wavelengths [3], [4], [10]. The wavelengths he worked with ranged from about 2.5 cm to 5 mm, corresponding to frequencies of 12–60 GHz [3].

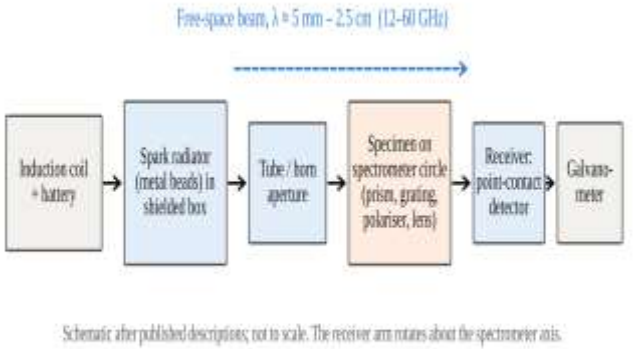


Fig. 2. Schematic of Bose's millimetre-wave apparatus, reconstructed from published descriptions. Not to scale.

The detectors evolved over time, from metallic contacts to the galena point contact that Bose patented in 1904 [3], [11]. The receiver was connected to a sensitive galvanometer. Everything except the galvanometer, and perhaps the induction coil, appears to have been made in Calcutta.

2. Precision Requirements

The most demanding measurement was the determination of wavelength by diffraction. For a grating of period d illuminated at normal incidence, the angle θ_m of the mth diffracted order satisfies

$$d\sin\theta_m = m\lambda \tag{1}$$

and an error $\delta\theta$ in reading the angle produces a relative error in wavelength

$$\frac{\delta\lambda}{\lambda} = \cot\theta_m \, \delta\theta \tag{2}$$

At a diffraction angle of 30°, an angular error of 0.5° (0.0087 rad) gives a wavelength error of 1.5%. Bose's receiver was mounted on an arm that rotated about the axis of a spectrometer circle, and angular settings to a fraction of a degree are readily achieved with a divided circle of modest size. The grating itself, however, must have strips spaced uniformly to a small fraction of the period. With periods of the order of a centimetre, a uniformity of a few tenths of a millimetre is sufficient, a tolerance within the reach of careful hand work with metal strip.

The tinfoil polariser illustrates how physical insight could replace precision machining. A stack of parallel conducting sheets separated by a distance s behaves as a set of parallel-plate waveguides. A wave whose electric field is parallel to the sheets can propagate between them only if its wavelength is shorter than the cut-off wavelength

$$\lambda_c = 2s \tag{3}$$

so that for $s < \lambda/2$ that polarisation is reflected while the perpendicular polarisation passes freely. For a wavelength of 5 mm the sheets need only be closer than 2.5 mm, a condition that the pages of a book satisfy many times over. An ordinary book interleaved with tinfoil therefore made an efficient polariser without any special fabrication.

The point of the analysis is that the millimetre-wave regime was well matched to the resources of a Calcutta workshop. Optical gratings for visible light require rulings accurate to a fraction of a micrometre and were made by only a handful of specialist establishments. At wavelengths a thousand times longer, the required precision falls by the same factor, into the range of ordinary metalworking.

Bose's choice of millimetre waves allowed him to perform optical experiments, on refraction, polarisation, total reflection and diffraction, with apparatus that he could build himself.

3. Design Philosophy

Two features of Bose's approach stand out. First, he scaled his apparatus to the wavelength. Dimensions of a few centimetres made the components compact enough to fit on a laboratory table, yet large enough to be fabricated accurately by hand. Second, he paid most attention to the element that limited sensitivity, the detector, and accepted simplicity elsewhere. His later move from physics to plant physiology carried the same habit. At the Bose Institute, founded in 1917, he developed recording instruments for the minute movements of plants, built in the institute's own workshop [12], [13].

VI. CASE TWO: RAMAN'S BOWED-STRING APPARATUS

1. The Problem

When Raman began work at the IACS in 1907, one of his first major programmes concerned the mechanics of bowed strings and the instruments of the violin family [5], [14]. Helmholtz had shown that a bowed string vibrates in a characteristic manner, now called Helmholtz motion, in which a single corner travels around the string. Its fundamental frequency is that of the free string,

$$f_1 = \frac{1}{2L}\sqrt{\frac{T}{\mu}} \tag{4}$$

where L is the vibrating length, T the tension and μ the mass per unit length. Raman developed a mechanical theory of the motion, including the effect of the bow's position and force, and tested it with experiments, among them a mechanical bowing apparatus that allowed bow speed, force and position to be controlled independently [14], [15].

4.2 Precision requirements

One of Raman's results was that there is a minimum bow force below which the Helmholtz motion cannot be maintained, and that this minimum increases rapidly

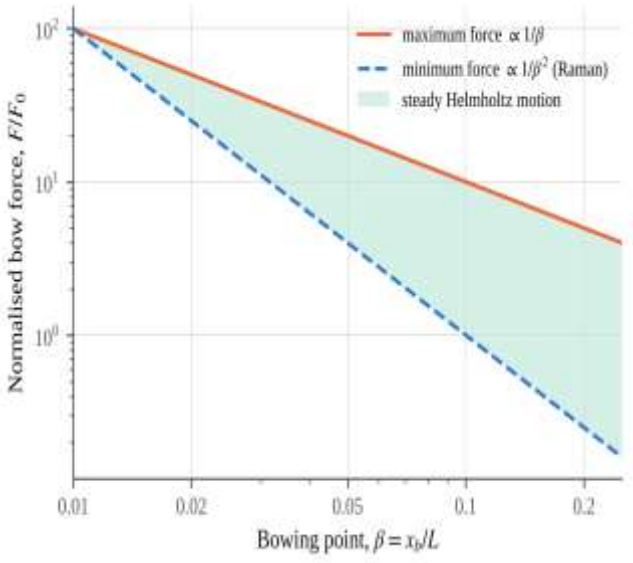
as the bow is moved towards the bridge. Schelleng later combined Raman's minimum with a maximum bow force, above which the string fails to release cleanly, into a now-classic diagram [16]. In Schelleng's form,

$$F_{\max} = \frac{2Z_0 v_b}{\beta(\mu_s - \mu_d)}, \qquad F_{\min} = \frac{Z_0^2\, v_b}{2R\,\beta^2(\mu_s - \mu_d)} \tag{5}$$

where β is the distance of the bowing point from the bridge as a fraction of the string length, v_b is the bow speed, Z_0 is the characteristic impedance of the string, R is the resistance presented by the bridge and body, and μ_s and μ_d are the static and dynamic coefficients of friction [16]. The ratio of the two limits,

$$\frac{F_{\max}}{F_{\min}} = \frac{4R\beta}{Z_0} \tag{6}$$

is proportional to β. Fig. 3 shows the playable window in normalised form. Near the bridge the window between the minimum and maximum forces becomes narrow, and a mechanical player must hold the force within a factor of a few. Far from the bridge the window is wide and the force is uncritical.



Z0/4R

vb

VIII. CASE THREE: THE LIGHT-SCATTERING EXPERIMENTS OF 1921–1928

1. The Apparatus

Raman's programme on the scattering of light began after his voyage to Europe in 1921 [5]. Over the following years he and his students studied the scattering of light by liquids, vapours and solids. The decisive observations of February 1928 were made with an arrangement of striking simplicity (Fig. 4). Sunlight was concentrated into the scattering liquid by a telescope objective and a short-focus lens. A blue-violet filter placed in the incident beam was combined with a complementary yellow-green filter placed in the path of the scattered light. If scattering did not change the colour of the light, nothing would pass the second filter. Raman and Krishnan found that a weak glow persisted, showing that part of the scattered light had a changed wavelength [18]–[20]. Within days they replaced sunlight by a mercury arc and examined the scattered light with a spectroscope and then a spectrograph, which showed sharp new lines displaced from the mercury lines by amounts characteristic of the scattering substance [21]. The same effect was observed independently in quartz by Landsberg and Mandelstam [22].

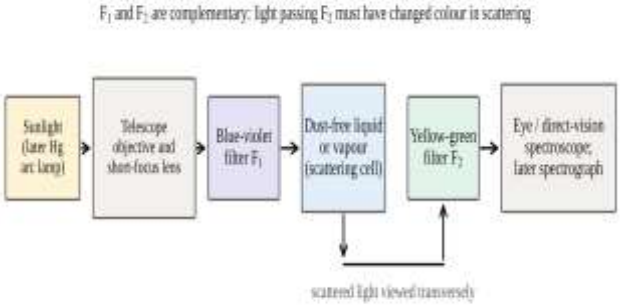


Fig. 4. Schematic of the complementary-filter arrangement used by Raman and Krishnan in February 1928. Not to scale.

IX. PRECISION REQUIREMENTS

The new lines are displaced from the exciting line by a fixed wavenumber shift $\Delta\tilde{\nu}$, so that the wavelength of a Stokes line is

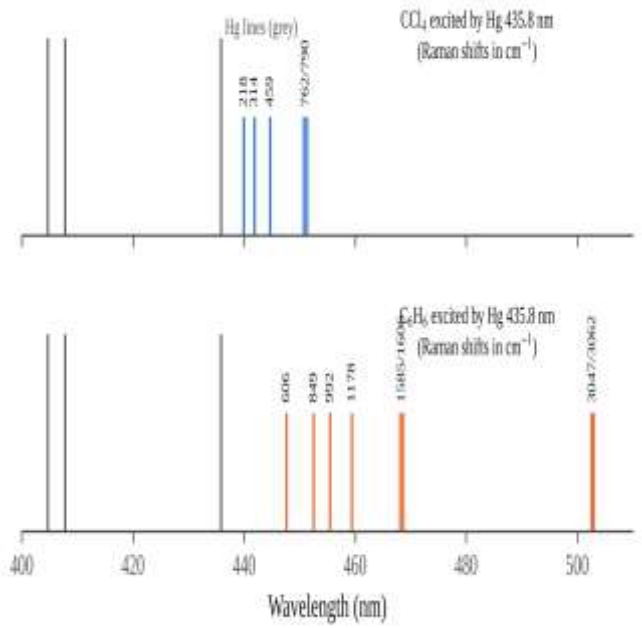
$$\lambda_s = \left(\frac{1}{\lambda_0} - \Delta\tilde{\nu}\right)^{-1} \quad (7)$$

where λ_0 is the exciting wavelength. Fig. 5 shows, from Eq. (7), the positions of the main Raman lines of carbon tetrachloride and benzene when excited by the mercury line at 435.83 nm, using their well-established shifts. The 459 cm^{-1} line of carbon tetrachloride falls at 444.73 nm and the 992 cm^{-1} line of benzene at 455.53 nm, about 9 and 20 nm from the exciting line.

Separating such lines from the mercury line requires only a modest spectroscope. The most closely spaced pairs are harder: the 762 and 790 cm^{-1} lines of carbon tetrachloride are 0.57 nm apart near 451 nm, and the 3047 and 3062 cm^{-1} lines of benzene are 0.38 nm apart near 503 nm. The resolving power needed to separate them is

$$\mathcal{R} = \frac{\lambda}{\Delta\lambda} \approx 790 \text{ and } 1330$$

respectively. A small prism spectrograph meets these requirements.



The real difficulty lay elsewhere. Raman scattering is extremely weak compared with the incident light and with ordinary (Rayleigh) scattering.

What the experiment needed was not high resolution but a large flux of exciting light, a scattering medium free of dust and fluorescent impurities, and a means of rejecting the unshifted light.

The complementary filters supplied the rejection; careful purification of the liquids, which Raman's students had refined over years of scattering measurements, supplied the clean medium; and the telescope objective supplied the flux [7], [19]. The precision of the 1928 apparatus was thus placed exactly where it was needed.

The importance of light-gathering can be made quantitative. For optics of a given focal ratio, the power that a lens concentrates from an extended source such as the solar disk into the scattering volume grows with the area of its aperture,

D

$$P \propto D^2 \quad (8)$$

It is instructive that Landsberg and Mandelstam, working independently in Moscow, observed the same effect with a different strategy, studying light scattered by crystalline quartz and recording the spectra photographically [22]. The physics could be reached by more than one route, but each route required the experimenters to identify and overcome the weakness of the scattered signal.

X. A COMMON DESIGN PHILOSOPHY

The three cases display a common pattern, summarised in Table 1. In each, the experimenters identified the quantity that limited the measurement and concentrated their effort on it, while meeting other requirements with simple means.

Table 1. Limiting quantities and precision requirements in three Calcutta experiments

Case	Limiting quantity	Required precision (estimated)	How it was met
Bose, millimetre-wave optics (1894–1900)	Detector sensitivity; angular measurement	Angles to a fraction of a degree; grating uniformity of a few tenths of a millimetre	Scaled apparatus; improved detectors; spectrometer circle
Raman, bowed strings (1910s)	Bow force near the bridge	Force within a window that narrows in proportion to	Mechanical bowing apparatus with controlled force and speed
Raman and Krishnan, scattering (1928)	Weak signal against intense unshifted light	Resolving power of about 10; high light flux	Large collecting optics; complementary filters; purified liquids

.

This is the approach that precision engineers formalise as error budgeting. The contributions of independent sources of error are estimated and combined, commonly as a root sum of squares

,

$$\delta_{\text{total}} = \sqrt{\sum_i \delta_i^2}\ \delta_{\text{total}} = \sqrt{\sum_i \delta_i^2}$$

so that the largest terms dominate and effort spent on small terms is wasted [23], [24]. Bose and Raman worked before this vocabulary was common, but their apparatus embodies its logic. Equation (10) also explains why a laboratory with limited resources could compete. Because the total error is dominated by its largest components, a laboratory that identifies and controls those components can match the performance of a better-equipped laboratory that does not.

A second element of the philosophy was the workshop itself. Bose's laboratory, Raman's IACS and later the Bose Institute each relied on in-house fabrication and on the skills of local mechanics [6], [12]. The workshop allowed rapid iteration: an idea could be built, tested and modified within days, as the rapid succession of experiments in February and March 1928 illustrates [20]. Imported instruments could not offer that speed.

XI. LESSONS FOR INDIGENOUS PRECISION MANUFACTURING

The history suggests four lessons for precision manufacturing in India today.

The first is to begin with the requirement rather than the tool. Both Bose and Raman decided what precision their measurement needed before deciding how to achieve it. Manufacturing programmes that aim to substitute imports often begin by acquiring the most precise machines available. An error budget of the kind in Eq. (10) shows where precision is actually needed and can reduce cost substantially, as the precision-engineering literature emphasises [23], [25].

The second is to scale the problem to available capability. Bose's choice of millimetre waves turned an impossible requirement for visible-light gratings into a tractable one for metalwork. Present-day designers can often make a similar choice, for example by using a measurement principle in which the critical dimension is larger, or by converting a dimensional requirement into one of force, time or frequency, which are often easier to control.

The third is to invest in in-house workshops and in the people who staff them. The skilled mechanics who built Bose's and Raman's apparatus were essential, yet their names are rarely recorded [9]. An indigenous precision industry requires trained instrument makers, toolmakers and metrologists, and it requires institutions that value them. University and research laboratories that maintain good workshops also train such people.

The fourth is to close the loop between measurement and fabrication. Raman's scattering apparatus and

Bose's detectors improved through repeated cycles of building and testing. Modern precision manufacturing relies on the same loop, now formalised through metrology and statistical control of processes [24], [25]. The cheapest way to make a precise part is often to measure and correct a less precise one.

A fifth lesson concerns documentation. Much of the tacit knowledge of the Calcutta workshops has been lost because designs, procedures and the names of the people who carried them out were not recorded systematically. Precision manufacturing depends on reproducibility, and reproducibility depends on written specifications, drawings, inspection records and standards to which parts can be made and checked. An indigenous precision industry must therefore build not only machines and skills but also the documentary infrastructure that allows skills to be transmitted and results to be reproduced from one workshop to another.

These lessons are not new to precision engineering, but the Calcutta laboratories show that they can be applied successfully in conditions of limited resources. That is perhaps their most important message for a country seeking to manufacture high-precision goods at competitive cost.

XII. LIMITATIONS

The reconstruction relies on published descriptions, which seldom give dimensions, materials or the names of the craftsmen involved. The precision estimates in Sections 3–5 are therefore requirements derived from the physics of the experiments, not measurements of surviving apparatus. Instruments preserved at the Bose Institute and at the IACS, together with laboratory notebooks and purchase records, could test and refine these estimates. The bow-force analysis uses Schelleng's later formulation of Raman's result with illustrative parameters, so Fig. 3 shows the form of the playable window rather than values for Raman's own apparatus.

XIII. CONCLUSION

Bose and Raman did internationally significant experimental physics in Calcutta with apparatus that was largely designed and made locally. An analysis of three cases shows that the precision their experiments required was modest in some respects and demanding in others, and that both men placed their effort where it mattered: on detector sensitivity and angular measurement for Bose, on the control of bow force for Raman's acoustics, and on light flux and rejection of unshifted light for the Raman effect. This design philosophy, supported by in-house workshops and skilled local craftsmen, remains a useful model for indigenous precision manufacturing: define the requirement, budget the errors, scale the problem to available capability, and invest in the people and workshops that close the loop between measurement and fabrication.

XIV. DECLARATIONS

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Data availability: All data needed to reproduce the results are contained in the manuscript; the parameter values and equations used for every figure are stated in the text.

Ethics approval: Not applicable.

Author contribution: The sole author conceived the study, carried out the analysis and wrote the manuscript.

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