

On Whispering Galleries

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(Plates I-V)

CONTENTS

- I—Introduction
- II—Description of the Gol Gumbaz at Bijapur
- III—The Victoria Memorial at Calcutta
- IV—The Granary at Bankipore (Patna)
- V—Whispering Gallery at the Calcutta G.P.O.
- VI—Propagation of Sound in Whispering Galleries
- VII—Synopsis

I. Introduction

In the volume of collected papers on Acoustics by the late Prof. W C Sabine published recently by the Harvard University, there is a very interesting article on 'whispering galleries' in which the architectural and acoustical features of several remarkable structures in Europe and America have been discussed. No mention is however made of whispering galleries in other parts of the world. Among the Indian whispering galleries the most notable, architecturally and acoustically, is the great Gol Gumbaz at Bijapur. In the Victoria Memorial recently completed at Calcutta, there are two very fine whispering galleries, one of which, curiously enough, remained unsuspected till it was discovered by the writer. There is also another whispering gallery at the Calcutta G.P.O., also first noticed and studied by the writer. The acoustical properties of the building known as the Government Granary at Bankipore in Patna District are also of much interest. The present paper contains a description of these whispering galleries. Other acoustical curiosities, such as Sekundar's tomb at Fatehpur Sikri near Agra, have been brought to the writer's notice, but they are not here discussed.

While in England in the year 1921, the writer in collaboration with Mr G A Sutherland of the University College, London, had an opportunity of carrying out a study of the well-known whispering gallery in the Dome of St. Paul's Cathedral at London, and the results of the investigation showed the presence, with a steady source of sound, of an interference-field in the gallery with radial

and circumferential nodal lines.¹ The comparative study of the three whispering galleries at Calcutta conveniently accessible to the writer has brought to light some further facts of interest relating to these structures. These are also discussed in the paper.

II. The Gol Gumbaz at Bijapur (see plate I)

“Transcending all other buildings at Bijapur in simple mass, and dominating the landscape for miles around, the great Gol Gumbaz or tomb of Sultan Muhammad,² stands alone (plate I). For size, few other buildings in India can be compared with it. Its noble proportions and magnificent dome are only seen to the fullest advantage from a distance. When close up to it, the dome seems to sink into the building, and to require an intermediate terrace or storey to raise it into full view. A few extra feet here would certainly have improved the general design, even when viewed from further off. The impressive grandeur of the building and its imponderable mass simply overwhelm the spectator with awe. It stands in the extreme east end of the city, its massive basement resting upon the solid rock. The vast mausoleum stands out with most striking effect when viewed, as Muhammad himself must often have seen it, from the upper hall of the Athar Mahall, when, backed by great storm clouds, the low western sun suddenly bursts through a rent and illumines the great building. It then flashes out into brilliant contrast against the rolling masses of angry black clouds; the mellow tints of its walls are bathed in a golden glow, and the great dome shines like burnished brass. Under all this glory peacefully repose the remains of Sultan Muhammad.

“King Ibrahim, his father, had raised the beautiful pile of the Ibrahim Rauza, which was the last word in decorative and luxurious magnificance. It was impossible for Muhammad to go further upon the same lines, so he struck out in a different direction altogether, and endeavoured to dwarf it, and everything else, by stupendous mass; and this he certainly accomplished. The Gol Gumbaz is the antithesis of the Ibrahim Rauza in that the strong virility of conception of the one contrasts with the delicate femininity of the other. His reign of thirty years, however, was not sufficient wherein to fully complete the building, for he seems to have died while the plastering of the walls was in progress, and it was no one else's business to complete what he left unfinished. One cannot help wondering what new departures would have been made in the further development of Bijapur architecture had the dynasty lived and flourished another hundred and fifty years, for they were daring builders.

¹ *Nature* (London), September 1921, and *Proc. R. Soc. London* 1921.

² King of Bijapur in Southern India seventh of the Adil Shahi Dynasty, from 1627 to 1656.

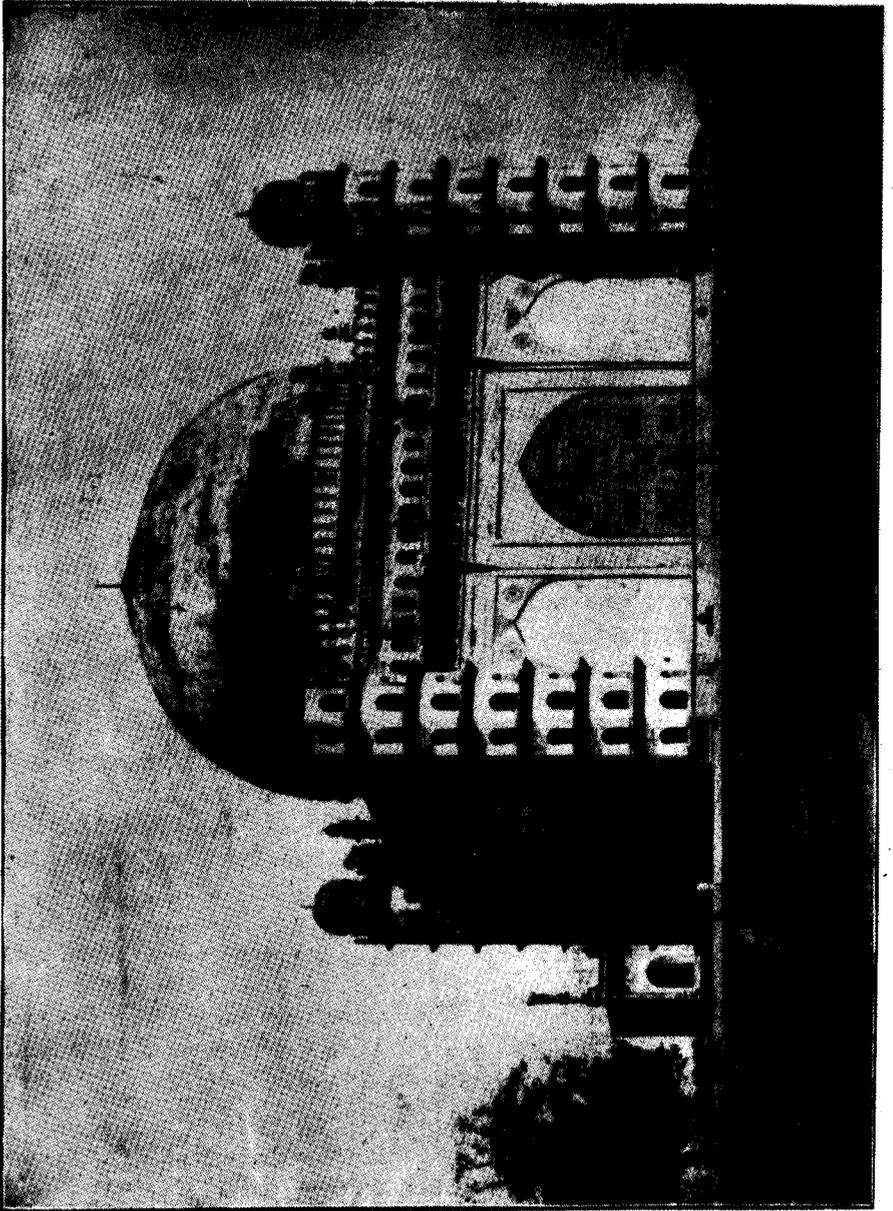


Plate I. The Gol Gumbaz at Bijapur.

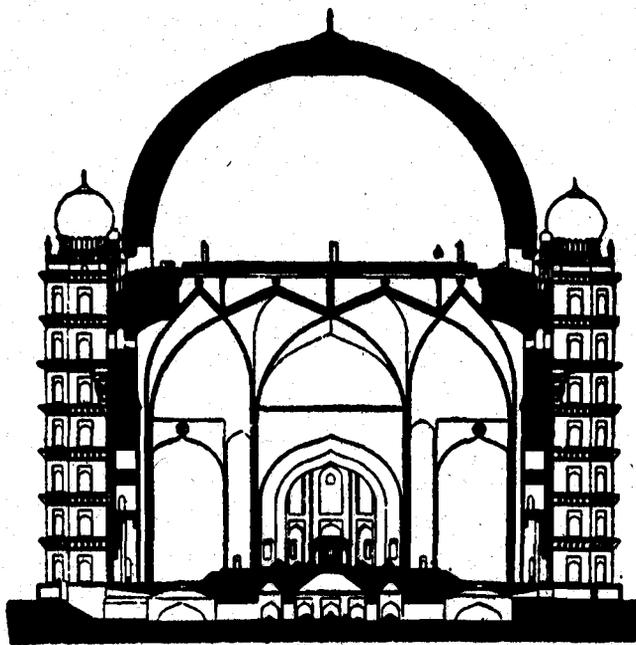


Figure 1. The Gol Gumbaz at Bijapur (Architectural Drawing).

“A glance at the plan (figure 1) of the Gol Gumbaz shows what a simple building it is for all its size—just a great square hall, enclosed by four lofty walls, buttressed up by octagonal towers at the corners, and the whole surmounted by a hemispherical dome. The great size of the dome, and the neat and perfect manner in which, by means of cross arching and pendentives, the square walls have been worked up to meet it, are the most notable features of the building. The extreme outside measurement of the mausoleum including the towers is 205 feet square. The extreme height to the apex of the dome from the base of the building is 198 feet 6 inches; the exterior diameter of the dome is 144 feet while the interior diameter, measured 124 feet 5 inches; and the great hall, below, with no intermediate supports of any kind, inside its walls, is 135 feet 5 inches square. The interior height, from the level of the floor, around the tomb platform to the top of the dome is 178 feet. Within the base of the dome is a broad gallery, 11 feet wide, which hangs out into the interior of the building, 109 feet 6 inches above the floor. Narrow staircases wind up through the corners of the building where the towers join it, and passages lead out from them on to each of the pigeon-holed storeys of the towers. In the centre of the floor of the hall is a high platform upon which are the counterfeit domes, the real graves being in the vault underneath which extends over the whole length and breadth of the hall.

“Each of the four walls of the building had been raised as three great arches, the central one being wider than the two side ones, and these have been filled in with

rubble masonry in the side ones, and cut-stone in the central one. On the north side, however, the central archway had been left open, or had been subsequently opened, as a small chapel or chamber has been built against the wall here as an annexe, communicating through the arch with the great hall within. In the central archways of the other three sides are the doors and windows; but, even here, the filling in above the windows can only be called crazy or patchwork-masonry. The masonry of the great dome may be looked upon as practically concrete it being composed of bricks in mortar, the thickness of the shell varying from ten feet at the springing to nine feet near the crown. It is thus a great rigid concrete shell without voussoirs, and, consequently, with practically no side thrusts of any kind so long as it remains intact. It is a dead weight acting vertically downwards partly upon the cross arching within and partly upon the side walls just as an inverted china basin would act upon the upper edges of a cube upon which it might rest. Being built in this way, with ring upon ring of thick brick work, each corbelled forward until they close at the apex, it is probable that no centering or support was needed beneath it during construction, except, perhaps, for a small section near the crown, which would have been supported by that part of the dome already built. An outward thrust that could possibly come upon the side walls would be amply neutralised by the weight of the material in the pendentives which hang over inside the building.

"This system of pendentives is, without doubt, the most successful and most graceful method of construction for such domes. It obviates any interference with the external contour of the dome, and adds, at the same time, a very pleasing feature to the interior—the interlacing or groining of the arches. The tendency of the dome to spread at the base, which is counteracted by the pendentives and great mass of masonry thus thrown into the interior of the building, was guarded against, in case of the Pantheon at Rome, which possesses a dome of greater diameter, by the heaping up of masonry upon the haunches of the dome outside, thus destroying its beauty of outline.

"The great hall below, which is covered by the dome, covers an area of 18,337·67 square feet, from which if we take 228·32 square feet for the projecting angles of the piers carrying the cross arches, which stand out from the walls into the floor, two on each face, we get a total covered area, uninterrupted by supports of any kind, of 18,109·35 square feet. This is the largest space covered by a single dome in the world, the next largest being that of the Pantheon at Rome, of 15,833 square feet. If we add the pendentives to the actual dome, to which they naturally belong as part of the superstructure, this then becomes the greatest domical roof in the world".

"But, was not this great dome, after all, but an after-thought?..... Before the walls of the Gol Gumbaz had risen many feet, it would seem that the plans were altered. The daring spirit of the architect, urged on perhaps by Sultan Muhammad himself, incited him to attempt the more stupendous task of hanging a mighty dome right across the whole expanse of the outer walls; and it seems

almost incredible that the man who conceived, and carried to such a successful issue, this magnificent project, should have passed into oblivion; his very name is unknown”.

“Another remarkable feature in the building is its whispering gallery, which runs round, inside the dome, at its base. Access is gained to it from the terraced roof around the base of the dome, by eight small door ways through it. As may be seen from the section (figure 1) it hangs out into the building, being supported upon the crowns of the cross arches below; and it is about eleven feet wide, inside the low parapet wall which protects it. On entering the building a person is struck by the loud echoes which fill the place in answer to his footfall; but these sounds are intensified on entering the gallery. The footfall of a single individual is enough to wake the sounds as of a company of persons, and, in response to ordinary conversation, strange weird sounds and mocking whispers emanate from the wall around. Loud laughter is answered by a score of friends safely ensconced behind the plaster. The slightest whisper is heard from side to side, and a conversation may be easily carried on across the diameter of the dome, in the lowest undertone, by simply talking to the wall, out of which the answering voice appears to come. A single loud clap is distinctly echoed ten times.”

The foregoing description extracted from the volume on Bijapur architecture by Mr Cousens published in the Indian Archæological Survey series makes it clear that the whispering gallery at the Gol Gumbaz is a very remarkable one. The present writer has not yet had an opportunity of visiting it but hopes it will soon arise. It is clear that the architectural features of this whispering gallery are distinctive, situated as it is at the foot of the dome itself, instead of in a drum below it as at St. Paul's, and a fuller study of the acoustical results following from this feature would be well worthwhile. Judging from the case of the whispering gallery at the Victoria Memorial, Calcutta, to which reference will be found below, it is not improbable that in addition to the usual circumferential propagation of sound-waves round the gallery, there will also be found a local concentration of sound at the further end of the diameter at which the source is situated. Mr Cousen's description indeed suggests that such an effect is present in a notable degree.

III. The Victoria Memorial at Calcutta (plate II)

The Hindu and Moslem Rulers of India left behind them great architectural monuments which impress the imagination of the beholder, and, in not a few cases, are gems of perfection which command the admiration of the world, e.g. the Taj Mahal. Though not on the same level as these triumphs of indigenous art in greatness of conception or execution, the Victoria Memorial recently completed at Calcutta, may, nevertheless, claim to be the most remarkable building of any erected in India during the years of British Rule and it is certainly an ornament to

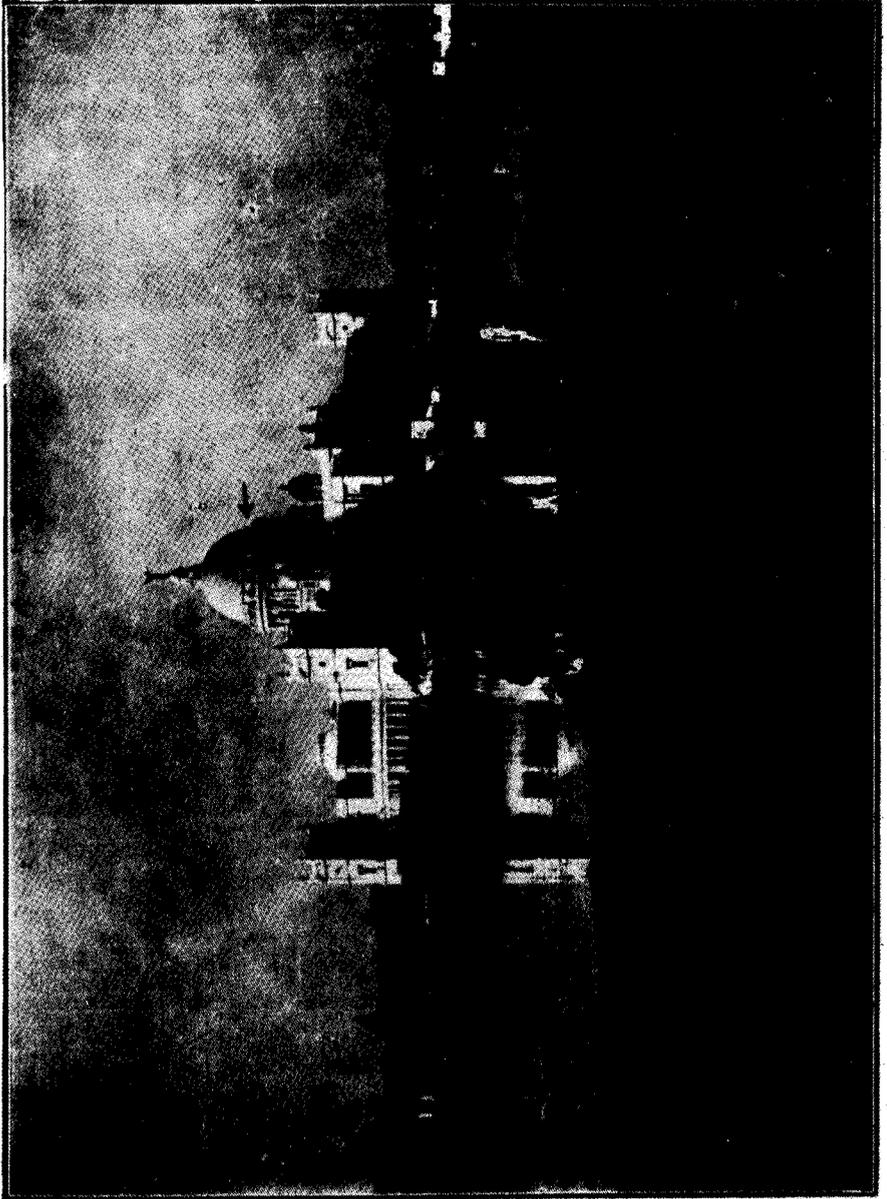


Plate II. The Victoria Memorial at Calcutta.

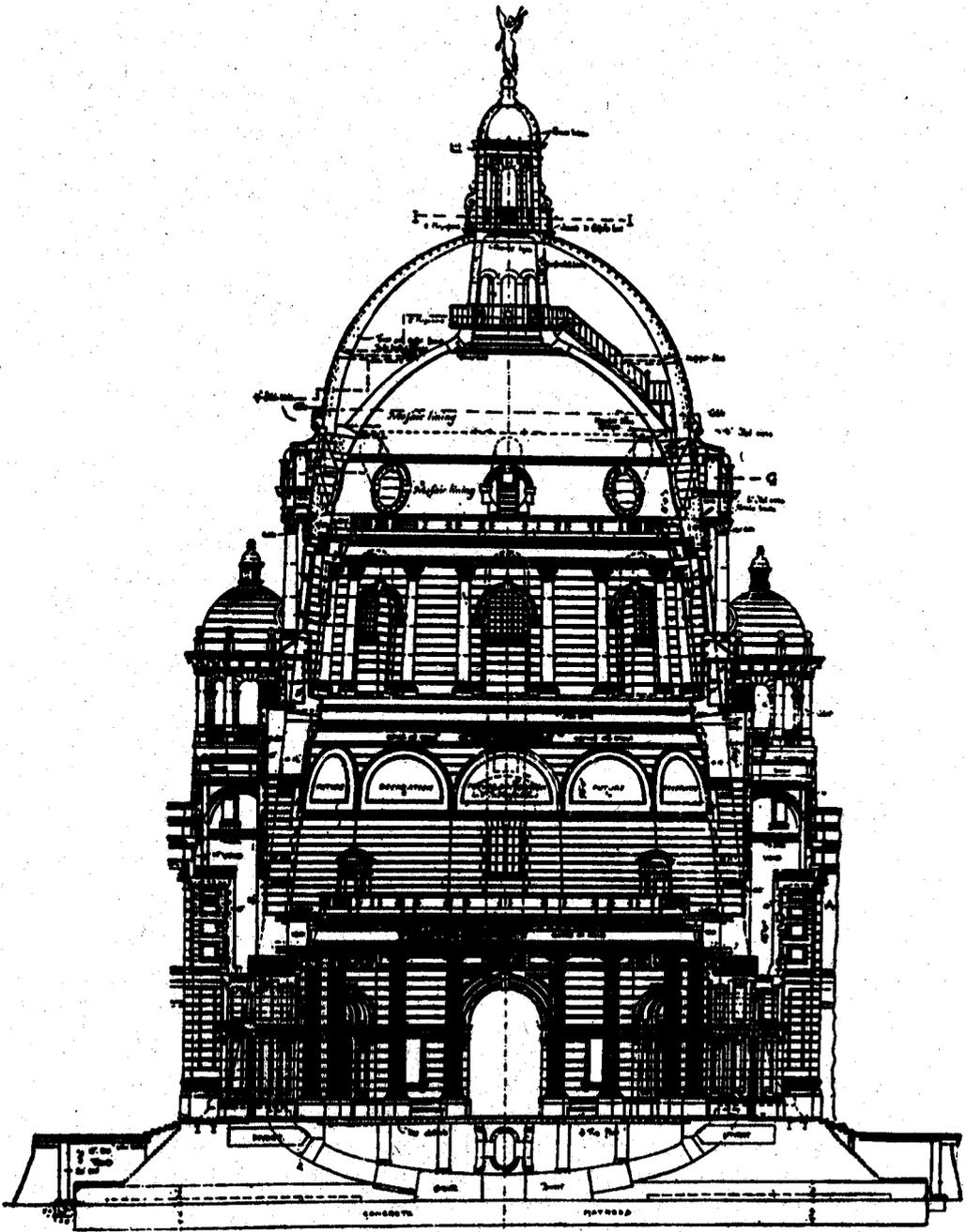


Figure 2. Section of the Victoria Memorial showing double dome.

the "City of Palaces". Occupying a privileged position in the Maidan or open space between Fort William and the city, this edifice of white Indian marble with its dome and winged statue of victory crowning all, catches the eye from afar and is a worthy monument of the reign of the Queen whose memory it seeks to perpetuate. The building took twelve years to construct and cost over half a million sterling. It is intended to be a treasure-house for historical paintings, sculptures, and other relics, and stands in extensive grounds which are being laid out as a public garden with ornamental tanks and bridges.

Going up by the grand stair-case facing the Maidan towards the Ochterlony monument, and passing through the portico and entrance room, the visitor finds himself in the circular Queen's hall which stretches up from the floor to the base of the inner dome of the building. In the centre of this stands the statue of the young Queen Victoria. Some 35 feet up from the floor is a gallery with its walls forming a dodecagon and above this, on the wall, twelve semi-circular spaces covered with paintings representing her life. Still higher, some 95 feet from the floor, is a second circular-gallery four feet broad which lies just at the base of the inner dome and is surrounded by a marble railing. The circular wall of the gallery here has a very decided slope inwards and is interrupted some few feet above the floor of the gallery by seven great circular windows which are visible from outside and by the opening for the stair-case by which admission to this gallery is obtained. An opening is also provided above by which it is easy to enter the space between the two domes and pass round it by a circular footpath. The inner dome is open at the top to which access can be obtained by stairs. These features are indicated in the architectural section in figure 2.

The circular gallery at the base of the inner dome, and the space between the two domes form two very perfect whispering galleries, the former of which was first discovered by the writer. The diameter of the former is 59 feet and of the latter 56 feet. Their special acoustical features have been studied by the writer and will be referred to more fully in section V below.

IV. The Granary at Bankipore (Patna) (see plate III)

"At once the most prominent and the most curious building in Bankipore is the old Government Granary known as the Gola. This is a brick building, 96 feet high with walls 12 feet thick at the bottom, built in the shape of a beehive or half an egg placed on end, with spiral two stair-cases on the outside winding to the top; it is said that Jang Bahadur of Nepal rode on horse-back up one and down the other. This dome-shaped structure was erected sixteen years after the great Famine of 1770, as a store-house for grain, it being intended that the grain should be poured in at the top and taken out at the bottom through the small door there. Owing to a curious mistake on the part of the builders, these doors were made to open inwards. The following inscription is on the outside:



Plate III. The Granary at Bankipore.

“No. 1. In part of a general plan ordered by the Governor-General and Council, 20th of January, 1784, for the perpetual prevention of famine in these provinces, this Granary was erected by Captain John Garstin, Engineer. Completed the 20th of July, 1786. First filled and publicly closed by———.”

The store-house has never been filled and so the blank in the inscription still remains, while the opening at the top is closed by a great stone slab. It stands to this day the monument of a mistake. During the famine of 1874, a quantity of grain, which, if left at the railway station might have been injured by the rain was temporarily stored there, and in times of scarcity proposals are still made to fill it with grain. But the loss from damp, rats and insects renders such a scheme of storing grain wasteful and impracticable. This building, once intended to meet the requirements of the whole district in time of famine, is now only useful as a store-house for furniture. It is chiefly remarkable for its reverberating echo, which answers to the slightest sound, a whisper at one end being repeated at the other. It is a landmark for a considerable distance along the river and commands a fine view of the surrounding country.”

The foregoing description is taken from the Patna District Gazetteer. In September 1922, the writer paid a brief visit to Bankipore and looked over this building, but had no time to make a thorough scientific examination of its acoustics. This is obviously a task that ought to appeal to the physicists at the local University of Patna. The most striking acoustical feature that was noticed by the writer was the return of the sound from the walls of the building as a surprisingly loud single echo when the observer stood at its centre and uttered a syllable or two. This was evidently due to the curved walls acting as a concave mirror focussing the sound at the same point as its origin. When the observer moved away from the central position, the simple return of sound gave place to a multiple echo.

The interior of the building is rather gloomy, as it is lighted only through the four doors in its massive brick walls. Inside, the brick work is bare, and has not been plastered over. The surface of the wall is thus not particularly smooth. An attempt to carry on a conversation in a low undertone with another observer situated 90° off along the curved wall was only partially successful. A further thorough study of the acoustics of this structure would be well worthwhile in order to explain the formation of the curious echoes heard in it.

V. Whispering gallery at the Calcutta General Post Office (see plate IV)

This gallery whose acoustical properties were first discovered by the writer merits a brief description. The General Post Office is the most imposing building amongst the many stately piles that surround Dalhousie Square at Calcutta. It is crowned by a dome set on a high cylindrical drum, the upper part of which is

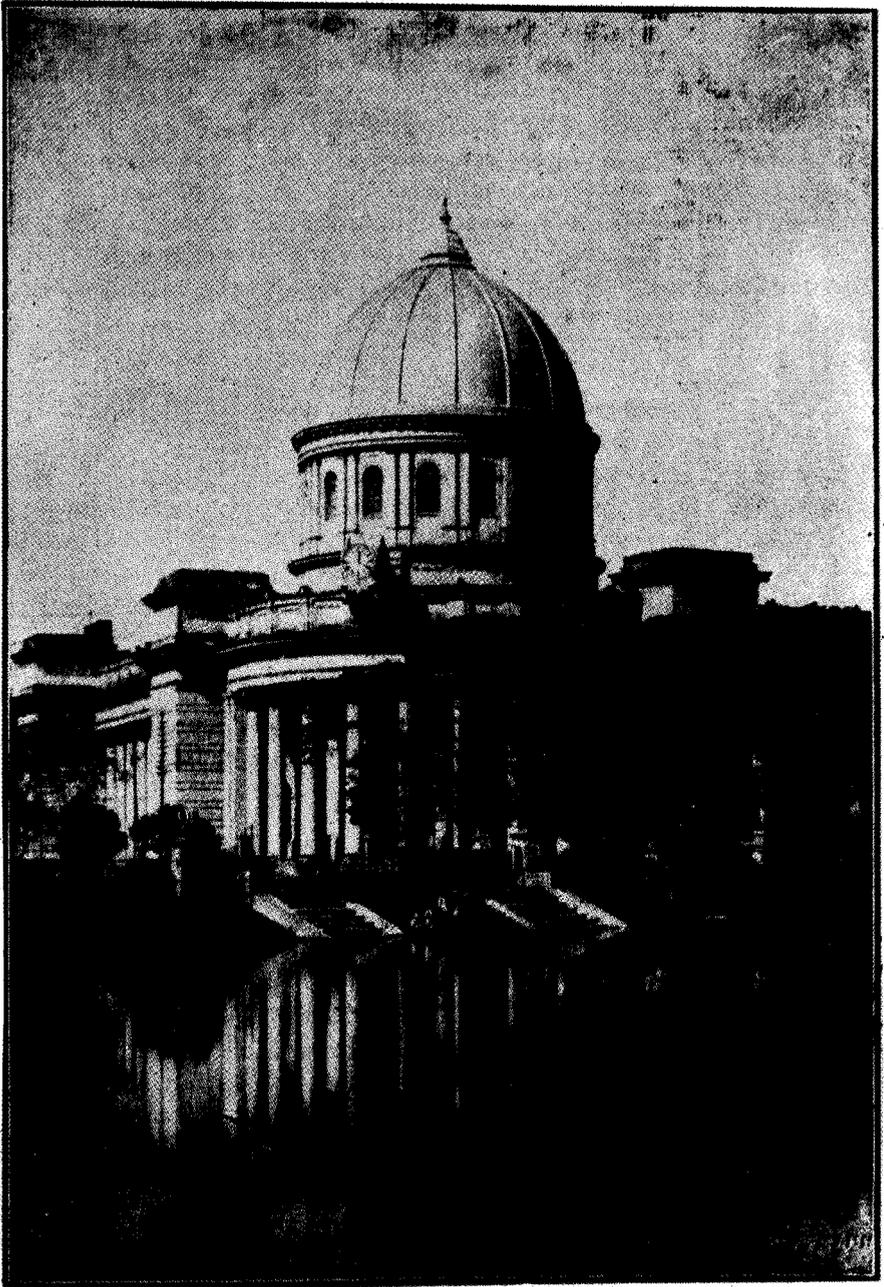


Plate IV. The Calcutta General Post Office.

occupied by a row of windows which illuminate the building; the lower part of the drum consists of a perfectly vertical smooth circular wall some fifteen feet high. This is provided with a gallery four feet broad to which admission is obtained through a single door, which opens in from the terrace of the building. The diameter of the gallery is 57 feet. Immediately below the gallery is the public rotunda. Unfortunately owing to the location of the building and one side of the rotunda being open towards Dalhousie Square, the drum of the dome is full of the hum of public traffic throughout the day. But early in the morning or late in the evening when the bustle of traffic had died away, the whispering gallery is fully worth a visit by the interested student of physics. It shows effects similar to those observed at St. Paul's though not in such a high degree.

VI. Propagation of sound in whispering galleries

The comparative study of the three whispering-galleries at Calcutta has yielded result of interest. The three galleries are approximately of the same size; the differences in their architectural characters are however considerable, and the differences in their acoustical characters consequent thereon are quite distinct. The gallery at the Calcutta General Post Office is architecturally very similar to that at St. Paul's in London, though smaller in size, with the important difference that its walls are perfectly vertical while those of the St. Paul's gallery slope distinctly inwards as has been pointed out by Prof. Sabine in his article. The fact that the effects observed in the latter are clearly more striking appears to support Prof. Sabine's contention that the inward slope of the wall is an important feature contributing to the efficiency of the whispering gallery.

The lower gallery at the Victoria Memorial whose acoustical features were first observed and studied by the writer has quite distinctive features of its own. This gallery is just below the inner shallow dome, and its wall is broken by eight large openings. In fact the continuous part of the wall above the floor of the gallery is only three feet high. Nevertheless, the gentlest whisper at any part of the wall is heard right round the gallery, particularly if the observer and his assistant stoop down a little towards the floor. The effect is hardly less striking than that observed at St. Paul's. As the wall of the gallery has a very marked slope inwards, this appears to furnish further support for Prof. Sabine's views. Part of the effect is however doubtless due to the presence of the curved surface of the dome above, of which indeed the wall of the gallery practically forms a part. If the observer and his assistant both stand up to their full height, and face each other directly, it is distinctly easier to converse in an undertone when they are at the opposite ends of a diameter than when they are a smaller distance apart.

The upper gallery at the Victoria Memorial which lies between the two domes naturally shows very striking effects, owing to the comparatively enclosed character of the space; the ease with a whisper anywhere is heard throughout is

distinctly uncanny, particularly as the observer and his assistant are hidden from each other by the mass of the inner dome. As will be seen from the architectural section, the wall of the gallery slopes pretty steeply inwards even at the lowest point.

Experimenting in these whispering galleries, the existence of circumferential and radial nodal lines in the acoustical field due to a steady source of sound was

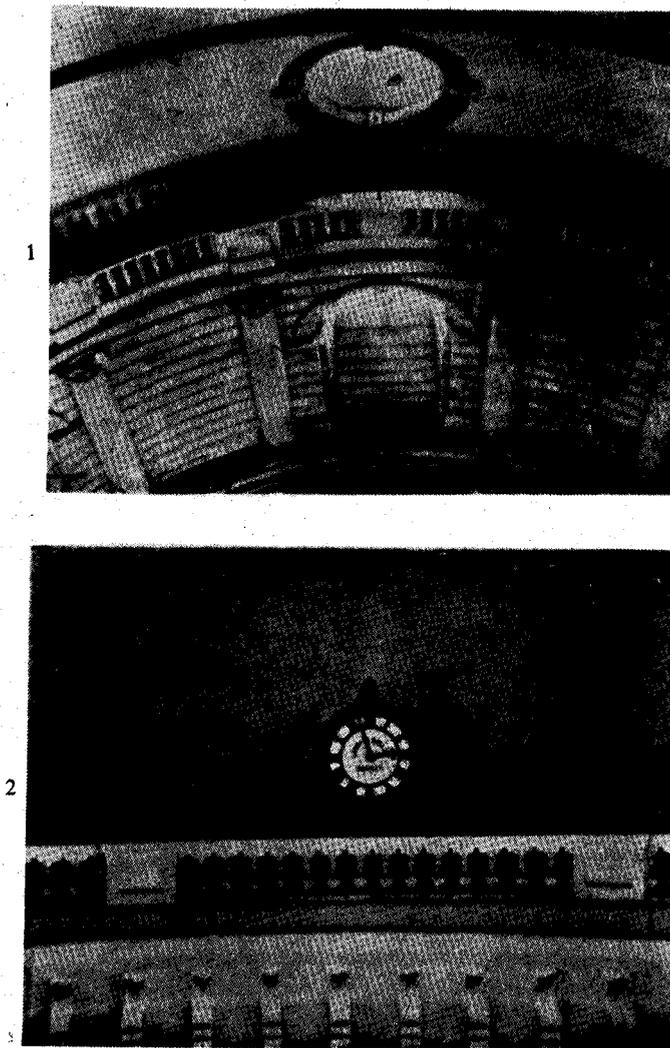


Plate V. (1) Part of circular gallery at the Victoria Memorial. (2) Part of circular gallery at the Calcutta General Post Office.

established as in the case of the St. Paul's gallery. Another interesting point to which the writer has not seen attention previously directed is the study of the propagation of sounds of an *impulsive* character in whispering galleries. Visitors to St. Paul's notice immediately the peculiar multiple echoes which accompany the sound of footfalls in the gallery; a single hand-clap is repeated five or six times. The echoes appear to proceed from somewhere near the opposite point of the wall of the gallery. Similar multiple echoes are noticed in the Calcutta galleries; the effect is least marked in the General Post Office gallery, much better in the lower gallery at the Victoria Memorial and appears in an extraordinarily exaggerated form in the upper gallery between the two domes, a single hand-clap or other sharp sound produced in the gallery being heard repeated no fewer than twenty times. As the observer producing the sound mounts the stair towards the top of the inner dome, the effect becomes less and less striking and ultimately vanishes at the centre. These observations give the clue to the real nature of the phenomenon; the multiple sound is not due to any echo, but is merely due to the fact that a sound-wave generated at any point on the gallery travels circumferentially round and round the gallery many times and is heard each time it passes the observer before it finally ceases to be audible. The smaller the decrement of intensity between two successive returns, the greater is the efficiency of the whispering gallery. The character of the sound at each successive return also undergoes a distinct alteration, as of course is to be expected owing to the differing decrements for sounds of different pitch.

The foregoing simple explanation of the multiple sounds heard in whispering galleries was verified in two ways. Firstly, if the origin of the sound and the observer are situated at different points in the gallery, the sound waves moving in opposite directions would pass the observer at different instants, and two sets of multiple sounds should thus be heard except when the observer and the source are exactly at opposite ends of a diameter. This was actually found to be the case, and the relative intensities of the sounds and the points of the gallery from which they appeared to emerge showed curious variations as the position of the observer was shifted.

The second method of verification was to determine the time interval between successive returns of the sound. With a little practice, this could be done in all the three galleries and was a particularly easy task in the upper gallery of the Victoria Memorial. By giving a tap periodically say at each tenth return of the sound, the succession could be kept up indefinitely, and the time taken for a few hundred returns of the sound could be determined with a stop-watch. The interval between successive returns of the sound was found to be equal to the circumference of the gallery divided by the velocity of sound, correct to within one per cent. It would be interesting to repeat this experiment in the larger galleries at St. Paul's and the Gol Gumbaz at Bijapur.

VII. Synopsis

The paper describes five whispering galleries: (1) the Gol Gumbaz at Bijapur; (2) the upper gallery between the two domes of the Victoria Memorial at Calcutta; (3) the lower gallery under the inner dome of the Victoria Memorial; (4) the Granary at Bankipore; and (5) the gallery at the Calcutta General Post Office. Of these (3) and (5) were discovered by the writer, and in quality, (3) is not greatly inferior to the gallery at St. Paul's at London.

The comparative study of (2), (3) and (5) has led to some interesting results, notably the confirmation of Sabine's view of the importance of an inward slope of the wall of the gallery for giving the best effects, and the concentration by a spherical dome of a maximum of sound at the opposite end of the diameter. Circumferential and radial nodal lines were observed in these galleries similar to those observed at St. Paul's. Further, the study of the propagation of impulsive sounds in these whispering galleries showed that the multiple sounds heard are not echoes as might be thought at first, but are due to the fact that the sound wave travels circumferentially round the gallery several times before it is sensibly extinguished, and is heard each time as it passes the observer. The smallness of the decrement in successive returns is a measure of the strength of the whispering gallery effect. The interval between successive returns is equal to the circumference of the gallery divided by the velocity of sound within an accuracy of one per cent. The waves travelling in opposite directions round the gallery can be differentiated by ear.