Balinese Gamelan Tuning: The Toth Archives

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THE study of gamelan tuning has flowed along two streams. As a living practice—the first and most immediate sense of "study"—the art of gamelan tuning is centuries old and wide-ranging in interpretation, application, conceptualization, terminology, and regional style. Knowledge bearers and practitioners, including *pande gong* (gamelan smiths), tuners, and musicians, often family or village based and multigenerational, have appeared in many centers in Java and Bali. The diversity of their practice, understanding, and technical approaches is enormous, paralleling (and interdependent with) the diversity of musical styles, genres, and instrumentation.

The second stream of study—the analysis of tunings by outsiders, mostly hailing from the world of Western scholarship—has often overlooked or sidelined these Indonesian sources. Indeed, works of Western scholarship form the bulk of citations in the literature. These include Ellis's "Tonometrical Observations on Some Existing Non-Harmonic Musical Styles" (1884); the work of two prominent figures of early ethnomusicology, Jaap Kunst (1949) and Mantle Hood (1966); the first comprehensive English-language study of Balinese music by composer Colin McPhee (1966); and work by later writers such as Rossing (1982), Rahn (1996), Tenzer (2000), Sethares (2005), and Jones, Gee and Grimshaw (2010)—some of whom sought to correct the perceived shortcomings of earlier writers. Most have based their studies on tone measurements, implicitly regarding gamelan tuning as a fully realized system of frequencies and relationships, analyzable on its own quantitative terms.

These two streams of study are not isolated. McPhee, for example, spent many years in Bali, and understood the performance practices of Bali deeply and broadly through extensive interaction with musicians, which emerges in his writings with clarity. Indonesian researchers such as Surjodiningrat et al. (1972) and those at Universitas Udayana (1986, 1988, 1989) have undertaken tone measurements of complete gamelan, using techniques and analysis similar to those of outside researchers. Yet, the imbalance in the published literature on tuning clearly tilts toward a data-centric approach, with relatively little consideration of the intent, conceptions, and living practice of tuning practitioners.

For that reason, Andrew Toth holds a special place in this canon. Not only did he carefully measure the pitch of every key and gong-kettle of 49 complete gamelan gong kebyar, carefully selected from all over Bali, but he also engaged in extensive interviews, discussions, and observations of tuners over many years. He sought to understand their work as a practice, utilizing conceptualizations in octave treatment, tuning profiles (i.e., conceptual models of intervallic relationships), and intent—the musical and sonic goals of various tuning strategies. In addition, he sought to convey this knowledge to both Balinese and outside researchers. His most extensive paper on the topic is written in Indonesian and was published in the journal

Mudra in 1993 by STSI, the Indonesian Arts Academy (Sekolah Tinggi Seni Indonesia).

In presenting and analyzing Toth's work, we offer our own two perspectives, from ethnographic research, performance, and the active practice of gamelan tuning (Vitale) to music theory and acoustic-engineering (Sethares). Since both authors, and Toth himself, approach the topic from a grounding in the tools of Western music—especially, in the long analytical traditions centered on scales, intervals, ratios, frequency measurements, and associated concepts—we position these findings primarily in that realm. We seek to advance understanding of a tonal system that fundamentally contrasts with Western, harmonically based tunings; this requires shattering certain assumptions that are implicit within those frameworks. We also wish to highlight the ideas and approaches of tuning practitioners, extending Toth's work. Whether and how these findings contribute to the practice of gamelan tuning in Bali are open questions, since the ways in which the two streams will intertwine in the future remains to be seen. They may be guided by technical or cultural factors not yet visible.[1]

The Work of Andrew Toth

Andrew Toth's (1948–2005) particular interests in ethnomusicology were already evident by May 1968, when he wrote an undergraduate essay at Wesleyan University entitled "Indonesian Music and Related Arts as a Realization of Cultural Ideals." He taught Javanese gamelan to school children in Wesleyan in the summer of 1970. In 1973, as a teaching assistant at UCLA, he wrote a grant proposal to travel to Bali to study the stylistic variations, geographical diversity, and instrumental tunings of *gender wayang* music. One of his goals for future work was summarized in the conclusion, page 9 of his 1974 paper "The Pitch Gamut of Central Java," written for Prof. Crossley-Holland's graduate class Music 280:

> "What is really needed is a large number of tuning measurements of every key/gongchime/gong of each gamelan . . . of various strata (by geographical area, urban/rural, *pande* (gamelan smith) or *pande* center. All pitches must be measured in order to get the complete tuning of the ensemble as well as of individual instruments. Perhaps a statistical approach might work well, since pitch and intervallic structure are fairly discrete, measurable quantities in a gamelan."

Indeed, measuring the frequency of every key, gong-chime, and gong of a large number of gamelan, and analyzing the results, would occupy Toth for the next decades of his life. In the PhD program at UCLA, he studied under Mantle Hood, played in several Indonesian

1. A simple example: While Toth and other researchers of that time (e.g., Universitas Udayana researchers) had to utilize a laborious method of tone measurement and frequency calculation to document tunings (Toth used a Hale Sight-O-Tuner, which can be accurate to about 0.1 cents in the hands of a skilled operator), frequency measurements can now be made with comparable accuracy using a smartphone running an inexpensive app (we used Peterson's iStroboSoft). Reproducing a tuning is also now relatively easy using digital devices, as *pande* in Bali occasionally do.

performing groups, and was appointed curator and archivist to the newly established Colin McPhee Collection (Harnish and Hardwood 2006).[2] He carried this interest in tunings through his various teaching and research positions, from Assistant Professor in Ethnomusicology at Brown University (1978–1983), to lecturer at STSI Denpasar (the National Arts Academy in Bali, starting in 1984), and during his spare time while he served as the United States Consular Agent in Bali (1989–2003).[3]

We first read about his measurements in his 1980 paper "Representations of Balinese Gamelan Tunings" (Toth 1980), where he mentions having measured, in 1975–76, the tunings of 49 complete *gamelan gong kebyar*. (The paper mentions fifty sets, but one was in fact a *semar pegulingan* and is not included here. Appendix B lists all 49 gamelan, along with a contemporary map of Bali showing their locations.) The *gamelan gong kebyar*, also known as *gamelan gong*, is an orchestra of bronze metallophones, tuned gong chimes, suspended gongs, flutes, drums, and cymbals requiring about 25 players. Created in the early twentieth century, the *gong kebyar* had, by mid-century, become Bali's most popular type of gamelan, with thousands of sets across the island (Vitale 2016). Toth used various criteria to choose which among these many gamelan to be measured, "combining lists of sets made by three well known musicians from different regions of the island" who considered whether each gamelan was "a famous one, kept well in tune, and by inclusion would help to provide equal representation for all the eight districts in Bali" (Toth 1980, 3).[4] In his 1993 article in *Mudra*, tuning data of three gamelan, from the villages of Getas, Sidakarya Tengah, and Gladag, are plotted in the form we now call *Toth Plots*. Unfortunately, he never published a comprehensive analysis or interpretation of the complete data set, the product of so many years of interest, field work, and thought.

When we learned that a collection of his papers was stored in the Special Collections section of Olin Memorial Library at Wesleyan University, we contacted the librarians and arranged a visit in January 2020. We scanned, photographed, and read through many of the papers and other documents of this archive. What emerged was a portrait of a man intensely focused on understanding the essence of the diverse, non-standardized tunings of Balinese gamelan, approaching the topic from many perspectives over a long period of his life. He minored in Chemistry, to better understand metallurgy and the bronze alloys from which

2. He also applied his skills in tuning measurement to the instruments of other cultures, e.g., American Indian flutes, as described in a March 1977 paper at UCLA (an unpublished class paper found in the Wesleyan archives).
3. At STSI (*Sekolah Tinggi Seni Indonesia,* which later became ISI, *Institut Seni Indonesia*), Toth was lecturer in research field methodology. The campus was only a couple of kilometers from his office as U.S. Consular Agent in the Renon area of Denpasar, and from his home in Sanur. It was also a short distance to the home of I Wayan Suweca, a noted gamelan tuner as well as Toth's long-time teacher and fellow performer of *gender wayang* music.
4. While inclusivity by regency (*kabupaten*) was a goal, none were included from the regency of Negara, perhaps because of the scarcity of *gamelan gong kebyar* in that region. See Figure 11, and Appendix B.

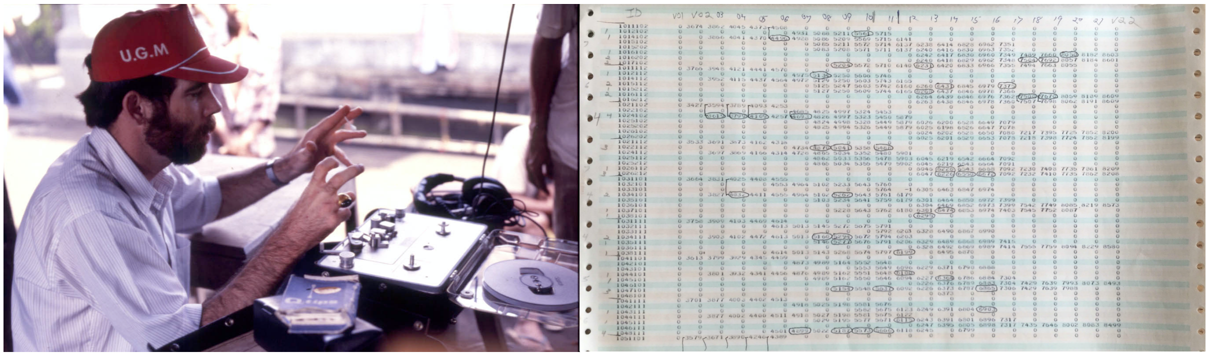

Figure 1. Left: Andrew Toth (circa 1977) with his Nagra IV-L tape recorder. Right: A typical page of the tuning measurements, with data encoded so that data for each instrument fit on a single line. Scans of all pages of Toth's *gong kebyar* measurements (such as the page above) are available in the electronic supplement to this article.

gamelan are made. His fluencies in Indonesian and Balinese, acquired over decades in Bali, allowed him to engage in conversations with many Balinese *pande gong* (gong smiths) and musicians. His love of recording—he owned a Nagra IV-L, a state-of-the-art field recorder at that time—enabled him to capture many tunings in the field for later analysis when on-site frequency measurements were not practical. He mastered statistical techniques, utilizing his skills in computer programming to analyze and search for patterns in the tuning data, as shown by many of the old-style, sprocket-fed, fan-fold, dot-matrix computer printouts (Figure 1) archived at Wesleyan. He also served as a generous personal gateway to Balinese culture for visitors, and his fascination with so many facets of Balinese music was widely known and respected (Harnish and Hardwood, 2006).

The information in Toth's computer printouts was not immediately clear or accessible. The hundreds of pages of measurements utilized four-digit numbers that were not frequency measurements, but some other form of encoding to make the data processing easy with the technology of that time. By cross-correlating the data with three published tunings from his 1993 paper, along with some educated guesswork, we were able to decode the meaning of the printouts. This process of decoding is described in detail in Appendix A. We translated the data into frequency values in Hz, and adopted a standardized spreadsheet format, available here.

Tuning Diversity in Bali

Before presenting and interpreting Toth's work, it is helpful to consider the issue of tuning diversity in Bali from a broad perspective. Rather than only describe or analyze it, we ask, Why does this diversity exist? What conditions or practices make it possible?

Many cultural factors are involved, but here we mention one central characteristic of gamelan that has deep consequences in the realm of tuning: its *indivisibility* as an orchestra. A gamelan is created as an integrated and, for the most part, inseparable set of instruments. Traditionally, they come from the same set of starting materials, are constructed together or in tandem by various craftsmen, assembled, tuned, and consecrated together with offerings and ceremony. These materials are consciously melded into a unified set, with a unique and complex identity. Indeed, we can think of a gamelan as a single meta-instrument with many parts, played by many people. The idea of taking out one of its components, such as a *pemade* or the *reong,* bringing it to a friend's home or a neighboring village, and combining it with instruments from another gamelan, is alien to the gamelan concept in traditional practice.[5] Aside from differences in tuning (which cannot be easily or quickly adjusted), the endeavor would clash on stylistic, visual, aesthetic, and even spiritual levels. An instrument *belongs* to one gamelan, not to others. This contrasts sharply with many ensemble traditions around the world, where it is an everyday occurrence for individuals to bring their own instruments, gather, tune to a well-defined external standard, and play.

There are exceptions and caveats to the principle of indivisibility for Balinese gamelan, which add dimensions to its identity. In modern Bali, the separate instruments and other component parts of a full bronze orchestra such as a *gamelan gong kebyar* are in fact no longer made together in a single shop. The sheer scale of the business has driven specialization of workers, workshops, smithies, villages, and regions.[6] Even after it is completed and delivered, a gamelan continues to change (as we shall explore below). Additional instruments might be added long after its original construction, in response to changing needs or standards. Wooden cases or other component parts, such as resonators, are often repaired or replaced. A broken key or cracked *trompong* pot is replaced by a new one, or melted and reforged to retain the original metal. The new parts are retuned as needed to match the set. In fact, a gamelan is never a static thing; over time it changes, but always retains, like a person, its individual identity (Yamin 2019) with tuning a central part of its dynamic change. In its first ten to twenty years, the internal crystalline structure of the high-tin bronze alloys used for gamelan gradually stabilizes, causing many of the pitches to rise, and the gamelan will require several tunings. Later, it may become quite stable, but tastes continue to change. Over the decades or even centuries of a gamelan's lifetime, many hands are involved in shaping its tuning beyond the *pande* who originally made it. Successive tuners might seek to restore it to its original tuning, but only in a general or subjective sense and not to exact frequencies. Others might consciously alter it, in response to changing needs, styles, or desires of the owners. Each tuner will have differing approaches and templates, absorbed within an oral tradition with changing technical resources (e.g., the use of machine grinders since the late twentieth century), without guidebooks or charts.

5. Modern composers and performers, working in experimental or so-called *kontemporer* styles, may break these boundaries, e.g., combining instruments of differing tunings or from different types of gamelan (McGraw 2013).
6. In South Bali, the bronze keys of a gamelan might be made in Blabatuh, the *reong* and *trompong* kettles in Tihingan, the large gongs in Semarang, Java, the wood cases in Gianyar, the drums in Getas, the carving done in Silakarang, and the painting back in Blabatuh when everything is assembled and tuned. During his time in Bali, Vitale has observed these subindustries that together make up a dense network of interconnected supply chains. A recent overview of this specialization in central Java is offered by Ludwig (2020).

The diversity of gamelan tunings can be seen as a consequence of the indivisibility principle. While many gamelan will be tuned similarly, a particular gamelan only needs to sound well in tune with itself. It demarcates and occupies its own internally integrated sound world. Without the necessity of conformity to an external standard, abundant variants have evolved, often in response to locally situated influences, such as ritual use and repertoire. Such diversity is prized aesthetically, as it is in many other realms of Balinese culture, for instance, the making of offerings. As we shall see in exploring Toth's data, *gong kebyar* tunings have regional characteristics, varying in overall pitch height, intervallic profile, and/or octave treatment. One writer has compared this diversity of style and region, and pride of local variation, to wine making (Hood 2015). We shall also explore historical change, comparing recent tuning measurements for five of the same gamelan that Toth measured in the 1970s.

KEY CONCEPTS: PAIRED TUNING SYSTEMS AND *OMBAK*

Aside from diversity, there are other challenges that Balinese tunings present for outside observers and musicians. Understanding them requires fundamental paradigm shifts for those accustomed to Western tunings, with their many assumptions about intervallic relationships. The characteristic intervals of Balinese tunings do not align to 12-tone equal tempered scales; indeed, these tunings (and the music itself) do not relate closely to harmonic systems in general, in which small-number intervallic ratios are idealized. Other principles are at work. While such intervals—a minor third (6:5 ratio) or fifth (3:2)—may occasionally appear, none are assigned special status; they are part of a wider spectrum of what Western music-trained observers would call "thirds" and "fifths" in gamelan tunings. In contrast, an interval approximately halfway between a minor and major second is common in both Javanese and Balinese gamelan traditions.

Even octaves, one of the most sacrosanct of intervals in harmonic tuning systems, often differ significantly from an exact 2:1 ratio, a fact that was so unexpected that early foreign researchers failed to notice or discuss it, as described below. In Bali, octaves are *tempered* through various strategies (Vitale and Sethares, 2020). This, and other aspects of Balinese tunings, arises as a direct consequence of the *paired tuning* system. The two partners of a paired unison are tuned to the "same" note—that is, are identified as the same scale degree—but are not tuned to the same frequency. Rather, unisons always come in two flavors, with higher (*pengisep*) and lower (*pengumbang*) partners, resulting in first-order beats between them. This is true for every scale degree in the gamelan. Stated differently, the unison (an exact 1:1 frequency ratio) is not an ideal in Bali; instead, unisons should beat prominently within the complete ensemble sound. These pulsations are aesthetically central to the Balinese sound world. Such beating is called the *ombak* ("waves"). The rate is not random or arbitrary, but is deliberately fixed and consistently applied. A *pande* or tuner establishes a desired *ombak* rate, typically about 8 Hz for a *gong kebyar,* and then keeps the *ombak* constant throughout the orchestra's complete multi-octave range. This rate—the distance between paired tones—is called *penyorog* by Balinese smiths and musicians.

Toth's trove of tuning data provides an excellent resource to explore the *ombak*: What is the true range of *ombak* values? How accurately are the paired instruments tuned? How consistent are the values? While gathering tuning data, Toth recorded whether each key was a *pengisep* or *pengumbang* as part of the ID code (in digit #6, as detailed in Appendix A). Thus, it is an easy task to gather all the *pengisep* and all the *pengumbang* values of a given note and average them. Figure 2 reports the average *ombak* values, along with their standard deviations, for all gamelan in the data set.[7]

As a result of this "constant *ombak*" principle, whereby the lowest pair of *jegogan* tones and the highest pair of *kantilan* tones should beat at the same rate, unisons and octaves enter into a fascinating interdependence, where exact 2:1 octaves are impossible to achieve on both members of a pair. As Toth (1980) noted, "if a constant beat rate is desired throughout the range of a set, one soon realizes that not all the octaves on the low instruments and on the high instruments can be tuned to a perfect 1200 cents." Figure 3 illustrates this interrelationship for a single scale degree and its octave, revealing the complexity of relationships involved.

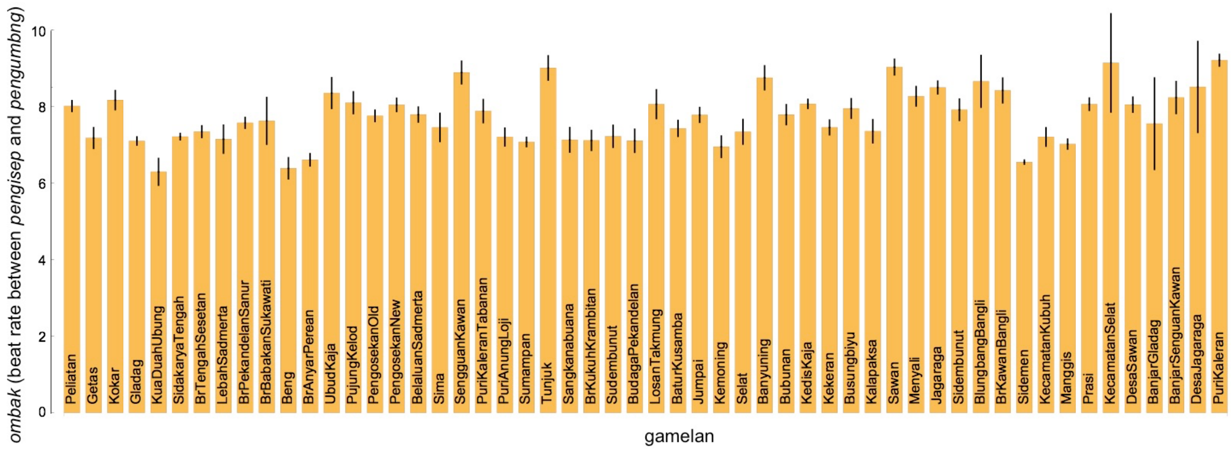

Figure 2. The *ombak* (beat rate) of all gamelan in the data set lies between 6 and 10 Hz, and individual gamelans maintain remarkably consistent rates internally, as shown by the error bars. These data are presented in the same order as Figure 11 and elsewhere.

pengisep	608	1216
pengumbang	600	1208

Figure 3. Assuming a constant *ombak* of 8 Hz between unisons and a pitch of 600 Hz for the lower (*pengumbang*) partner, octaves can be tempered in a variety of ways. In this example—one possible tempering—the *pengisep* shows an exact 2:1 octave relationship (608–1216). The *pengumbang* shows a stretched octave (600–1208). But when all four tones are sounded at once, which happens frequently with the many octave doublings in gamelan, other types of octaves arise through cross-relationships: a compressed octave (608–1208), and a very stretched octave (600–1216).

7. Figure 2 shows the 5% trimmed mean and 5% trimmed standard deviation. There are instances where individual entries are clearly incorrect. These may be due to measurement error, transcription error, broken keys, or other untraceable events.

GRIDS, GRAPHS, TABLES, AND OCTAVE PERCEPTIONS

It is possible to trace a long history of scholarship over the past century as outside observers, and more recently Indonesian researchers,[8] have documented gamelan tunings in Java and Bali by measuring frequencies. One of the first tasks for each was to graphically represent the tones, scale degrees, octaves, and ranges of all the instruments of a gamelan, which comprises hundreds of keys and *pencon* (the Balinese term for any knobbed, tuned gong or gong kettle). Kunst (1949) introduced the grid-based graphical method for a Javanese gamelan, with octaves, frequencies, and scale degrees shown along the top on the horizontal axis, and each instrument on the vertical axis, giving charts that look like Figure 4.

Figure 5 shows our rendition, of direct relevance for this study, graphically representing all bronze keys (134 on 16 instruments) and tuned *pencon* (22 on two instruments) in a *gamelan*

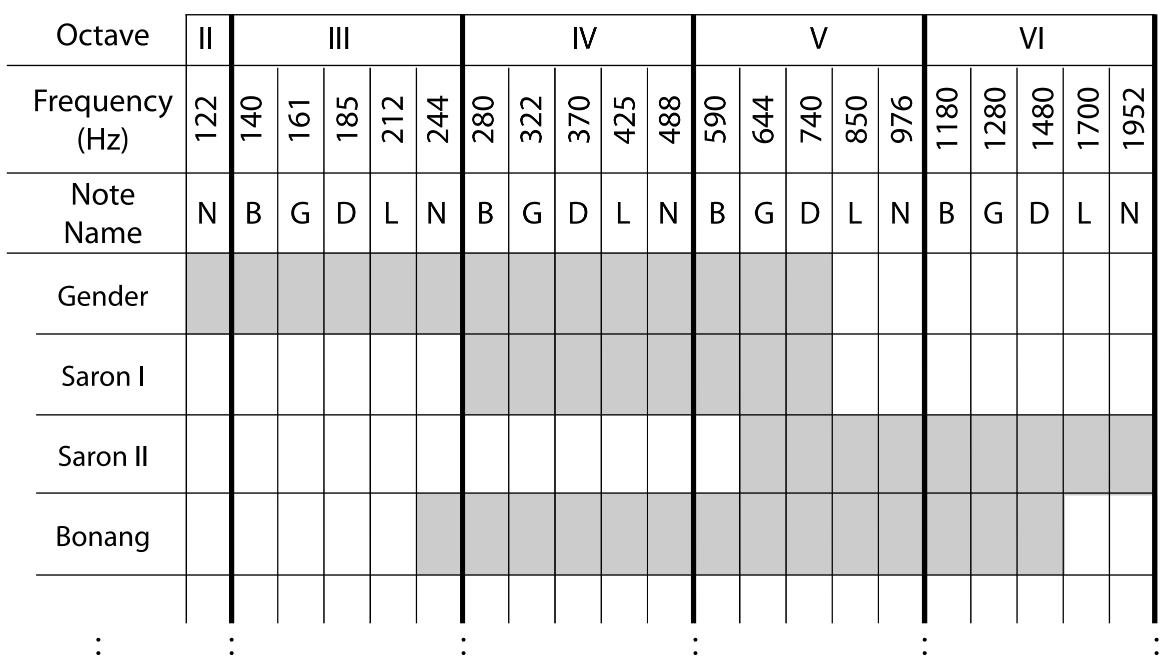

Figure 4. Kunst (1949) introduced a grid-based representation of tuning data of Javanese gamelan; this shows an excerpt in similar style. Each instrument has many keys or gong chimes, as indicated by the shaded regions. Like other early foreign investigators, Kunst likely did not measure all individual frequencies, but rather measured only a single octave span and then presumed that other octaves were tuned to 2:1 frequency ratios. Note names (scale degrees) are reported in Javanese solfège (B = bem, G = gulu, D = dhadha, L = lima, N = nem).

8. These Indonesian researchers include Surjodiningrat et al. (1972), the Universitas Udayana researchers in the Tata Nada series (1986, 1988, 1989), and Kartawan (2014), among others.

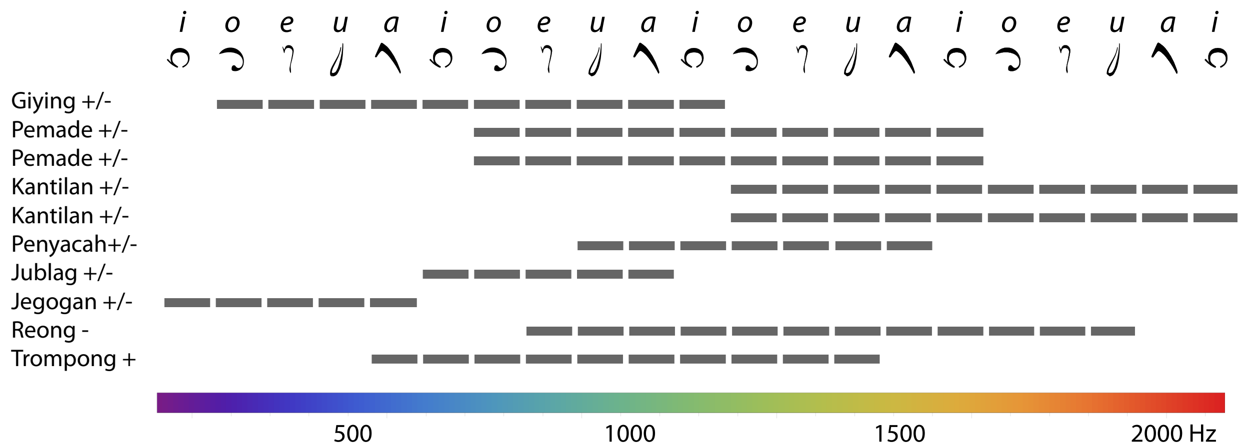

Figure 5. The instruments, ranges, and scale degrees of a modern *gamelan gong kebyar* in standard instrumentation. Each key and *pencon* (gong-chime) is represented by a small segment with pitches increasing from left to right along an approximate frequency axis. Scale degrees (d*i*ng, d*o*ng, d*e*ng, d*u*ng, d*a*ng) are shown in phonetic and in Balinese notation. Each keyed instrument is a member of a pair, with *pengumbang* (lower -) and *pengisep* (higher +) members. The *reong* and *trompong*, though fulfilling different musical roles, are typically tuned to *pengumbang* and *pengisep* respectively and may be regarded as a pair.

gong kebyar of current standard instrumentation.[9] Note that our analysis, like Toth's, is confined to the *tunable* instruments within the gamelan: it does not include the large suspended gongs (*gong wadon, gong lanang, kempur, bende*, and *kemong*) or other hand-held *pencon* (*kempli, kajar*), which, once made, are almost never retuned.[10]

Early analyses of gamelan tunings had particular shortcomings, which were gradually corrected or revised as studies and scholarship accumulated (Baumbusch 2017). Kunst (1949) failed to note any variability in octave treatment, assuming they were (or should have been) exact 2:1 octaves. McPhee (1966), in the first comprehensive treatise on Balinese music in English, illustrated intervallic relationships and variations—the "tunings" of several gamelan, in graphic comparison—only within a single octave, overlooking not only octave treatment, but also the ubiquitous use of paired tuning in Bali. A series of writers (Hood 1966, Erickson 1986, Rossing 1982, Vetter 1989, and Surjodiningrat et al. 1972, among others) gradually added

9. The instrumentation of a gamelan *gong kebyar* was codified into standard form only in the latter twentieth century, partly through the island-wide gamelan competitions (*Mrdangga Utsawa*) of the Bali Arts Festival (*Pesta Kesenian Bali*), a prominent forum for *kebyar* performance since the late 1960s. Festival rules, drawn up by government arts agencies, dictated the instrumentation of a "complete" *gong kebyar*, and the number of instruments per instrumental group as shown in Figure 4 (I Nyoman Windha 2020, personal communication with Vitale). Many of the 49 gamelan Toth documented, made long before the Bali Arts Festival existed, show instrumentation that varies from the current standard.

10. The various *pencon* that are normally not re-tuned, especially the large gongs, clearly contribute fundamentally to the sonic character of a gamelan, but a comparative analysis that includes them lies outside of the scope of this study.

more dimensions to the picture, including the fact that octaves within the complete range of a gamelan are deliberately stretched or compressed. However, none of these writers drew any direct connection between paired tuning and octave treatment in Balinese gamelan.

It was Andrew Toth who, through his tuning measurements and extensive interviews with gamelan makers and tuners, first described the interdependence between *ombak* and octave based on acoustic considerations, as described above and in Figure 3. Gamelan tuners use a variety of techniques to fine tune the instruments as shown in Figure 6. While Toth's two articles elucidated this and other key aspects of gamelan tuning, he never published a comprehensive analysis of his large and unprecedented data set before his death in 2005. Now, we have the opportunity to explore how the data reflect, quantitatively, these tuning concepts. These data are now all the more valuable, since they capture diverse tunings of Bali's ubiquitous *gamelan gong kebyar* at a particular historical moment in the 1970s. Many of these tunings, including those of famous gamelan orchestras, have since changed, subtly or more noticeably, through the effects of time and the work of successive gamelan tuners. By retaking measurements of a handful of the same gamelan sets, we can begin to study such temporal changes.

Figure 6. Interviews with smiths and workers who tune gamelans occupied Toth throughout his research. In this photo (from Toth archives, circa 1977) a tuner has just struck two keys and is holding them close to his ear to hear the *ombak*, counting the number of beats difference in the frequencies of the two keys.

VISUALIZING TUNING USING TOTH PLOTS

One of Toth's innovations was in the realm of data visualization. He created a way to display the tuning of a gamelan that clearly shows three of its dimensions: (1) The constant *ombak* rate as it manifests from low to high, producing wider unison pairs in the lower octaves and narrower ones in the higher ones; (2) the individual intervals of the scale steps, as proportionate distances along a horizontal frequency axis; and (3) the distinctive behavior of the octaves for each scale degree. Among other dimensions, these plots offered a visually immediate way to show how octave treatment varied from note to note within a single gamelan. We call these *Toth Plots* in his honor. Further, we use his visualization strategy, and the tools of modern computer-generated graphics, to present the tuning data for all 49 gamelan. This section describes how the raw tuning data are processed to draw Toth Plots and shows features of the tuning that can be seen in the individual plots. The following section shows how Toth Plots (and the data) can be used to infer both commonalities across many gamelan and idiosyncrasies of individual gamelan tunings.

We also follow the practice of Toth and other writers (e.g., Universitas Udayana 1986) in presenting tabular charts of the complete, raw frequency measurements. Even if duplicated or doubled by another instrument, the frequency of every key and *pencon* is included. Slight (or large) differences—their "out-of-tuneness"—are addressed through statistical analysis. Our tabular spreadsheets, available here, show the frequency (in Hz) of each key and *pencon* of all 49 gamelan according to Toth's measurements in the 1970s, plus the tunings of five of these gamelan in 2019. We commissioned Balinese composer I Made Arsa Wijaya to measure the contemporary tuning of five gamelan from Toth's original set.

Tuning data can be displayed in various ways. Here we describe, in a sequence of graphs and tables, the process of arriving at Toth plots. The first step involves segregating all the instruments into one of two categories, *pengumbang* or *pengisep*—much the same way that *pande gong* categorize them.[11] We then calculate the mean (average) value of the frequency of each of the 21 scale degrees throughout the range of the gamelan within each category. Some, at the extremes of high and low, have only a few representatives. Others, in the middle of the range where many instruments overlap, have more representatives. Thus partitioned, the result is a pair of scales that represent the underlying tuning of all the keys and *pencon* over the full 21-degree range. Assigning each pitch is relatively easy to accomplish because of how the frequencies are clustered: Individual keys or *pencon* typically do not differ from the *pengumbang* or *pengisep* average by more than 1 Hz (and often much less), while the *pengumbang* typically differs from the *pengisep* by a much greater amount, 7 to 10 Hz. Exceptions do appear of extremely out-of-tune keys or *pencon,* but their roles can be assigned from other notes on the same instrument. Figure 7 shows an example of this first step in the

11. This segregation into two groups is an important step in the process of making the keys and gong kettles. For convenience (and later reference), many gamelan makers scratch an X onto the back of all *pengumbang* keys and a line (/) onto the back of all *pengisep* keys.

octave		*i*	*o*	*e*	*u*	*a*
V	+	2361.6				
	-	2352.0				
IV	+	1151.6	1247.1	1384.1	1720.3	1853.9
	-	1141.9	1241.4	1374.3	1713.8	1846.4
III	+	575.0	609.4	673.2	852.9	920.4
	-	566.9	600.5	665.8	845.1	912.4
II	+	289.2	316.4	339.2	416.6	451.2
	-	281.9	308.5	331.3	407.9	443.3
I	+	144.0	160.1	176.4	212.4	228.7
	-	136.5	152.4	169.0	204.2	220.2

Figure 7. The tuning of all four octaves of the gamelan of Peliatan (Gunung Sari) showing averaged *pengumbang* (-) and *pengisep* (+) values for each of the scale steps *i*, *o*, *e*, *u*, *a*. Observe that the difference between + and – pairs is very close to 8 Hz across the full tuning range of the gamelan.

octave		*i*	*o*	*e*	*u*	*a*
V	+	4935.2				
	-	4928.3				
IV	+	3692.1	3829.9	4010.4	4386.8	4516.3
	-	3677.3	3822.0	3998.1	4380.3	4509.3
III	+	2489.7	2590.0	2762.6	3172.1	3304.1
	-	2465.0	2564.6	2743.3	3156.3	3288.9
II	+	1300.1	1455.1	1575.6	1931.5	2070.0
	-	1255.8	1411.8	1534.9	1895.3	2039.3
I	+	92.6	276.1	443.9	765.1	893.5
	-	0.0	190.2	369.7	697.7	828.3

Figure 8. The data in Figure 7 are transformed into cents referenced to the lowest *ding pengumbang.*

process, reducing the full set of measurements (156 frequencies) of the gamelan of Peliatan to a more manageable size.

To illuminate intervallic relationships, the *pengumbang* and *pengisep* scales are then transformed into cents (see Figure 8), using the lowest *ding* value (136.5 Hz for the lowest ding in the Peliatan gamelan of Figure 7) as the reference or starting point.[12] For example, *dong*

12. Choosing *ding* as the reference seems reasonable, but alternative perspectives are worth noting. *Ding* is the lowest tone in most, but not all, gamelan *gong kebyar*. (Two in Toth's data set start on *dong*, and eight, mostly from

pengisep in the lowest octave (160.1 Hz in Figure 7) is converted to the ratio 160.1/136.5 and then transformed into cents, giving 276.1 cents, about a quarter tone shy of a minor third in 12-tone equal temperament.[13]

The next step stacks the octaves of the *pengumbang* separately from the octaves of the *pengisep*. This is shown in Figure 9 where the two are distinguished by color.

The final step transfers the numbers in Figure 9 into the plot of Figure 10, maintaining the left-to-right relationship between *i*, *o*, *e*, *u*, and *a*, the up-down relationship between the

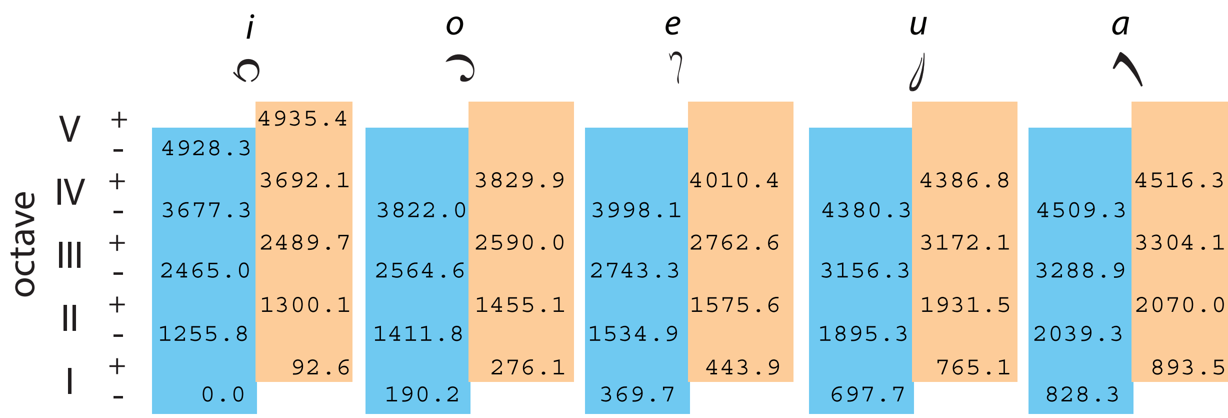

Figure 9. The *pengumbang* and the *pengisep* are color coded separately to emphasize the differential treatment of the octave.

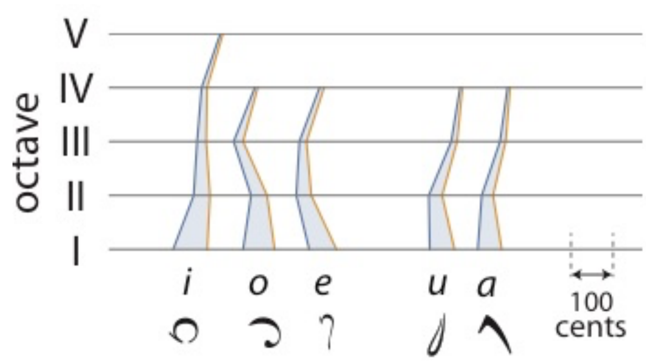

Figure 10. This Toth Plot represents the numerical values of the gamelan of Peliatan, as given in Figure 9. The horizontal direction shows the scale steps while the vertical direction shows how the scale steps vary with each octave. The coloring differences are maintained from Figure 8 for *pengumbang* (blue) and *pengisep* (orange).

North Bali, start on *dang*). Also, the instrumental groups of a *gong kebyar* show a curious democracy of lowest notes: at least one starts on *each* of the five scale degrees, which engenders ambiguities of melodic shape in musical realization. Most musicians today will sing the *pelog* scale starting on *ding*, but this may be a modern phenomenon since older ritual or court gamelan are not anchored in this way. Other scale degrees, which shift by mode in seven-tone music, may be the lowest on certain instruments (such as *suling*) and/or the most important in a given composition. In other words, *ding* is not the same as *do* (of do-re-me), in terms of functioning as the home or preeminent scale degree. See also Vitale (2002) and Tenzer (2000).

13. The formula to convert a ratio r to cents is 1200 $\mathrm{Log}_{10}(r)/\mathrm{Log}_{10}(2)$, which is approximately 1731.23 $\mathrm{Log}_{10}(r)$.

octaves, and the separation of the *pengumbang* in blue from the *pengisep* in orange. Thus each vertical spike shows how the scale steps of the *pengumbang* and *pengisep* vary by octave, from low to high.

INTERPRETING TOTH PLOTS

Several features of the Toth Plot in Figure 10 are immediately apparent. We can easily see, for example, the intervallic profile of the *pelog* scale by the horizontal spacing of the five tones. The scale steps appear as three clustered spikes (*i*, *o*, and *e*) separated from a cluster of two spikes (*u* and *a*). This generic feature of *gamelan gong kebyar* tuning is a simple consequence of the fact that it utilizes one mode, usually regarded as *selisir,* of the parent seven-tone *pelog* scale (McPhee 1966). The other two tones would be in the spaces, that is, within the larger intervals of *deng-dung*, and *dang-ding*. (The upper *ding* is not shown.)

The direction of the spikes—whether they lean to left or to right, or change direction upwards through the octaves—reveals octave relationships. If the octaves were exactly a factor of two (2:1) in the *pengumbang*, the blue line of a spike would be vertical. If the octaves of the *pengisep* were precisely 2:1, the orange line would be vertical. (Figure 14 shows such idealized octave treatments.) However, as these data show, the lines tend to lean and squiggle in various ways. When a spike, or part of a spike, has negative slope (leans to the left), the octave is compressed; when it has positive slope (leans to the right), the octave is stretched—with the caveat, as noted in Figure 3, that cross-relationships can produce simultaneities of compressed, perfect, and stretched octaves. All of these possibilities will be discussed in the next section, both relative to idealized octave tempering strategies, and in the actual profiles shown in the data. However, for the moment, we simply note one clear feature of the Peliatan plot as a typical case among all the Toth plots: *Octave treatment often varies from one scale degree to another*. This brings up important questions, explored below: What is "the tuning" of a particular gamelan? Is it possible to reduce a gamelan's tuning to a simple sequence of intervals? If so, which octave should be used to represent it? These questions challenge fundamental assumptions about tuning.

Another feature of the plot in Figure 10 is that the spikes tend to get narrower towards the top. This is a direct result of the constant *ombak*, since a rate of 8 Hz in the first octave (136 to 144 Hz for the *jegogan ding* in Peliatan) creates a span of about 90 cents, while the same 8 beat *ombak* rate creates a span of only 8 cents in the highest octave (2353 to 2361 Hz for the highest *kantilan* tone). Another way to state this is that cents represent a logarithmic relationship in a linear frequency variable. To illustrate, consider an extreme hypothetical case. If the range of a gamelan were extended down two more octaves below a typical frequency of 120 Hz for the lowest *jegogan ding* (*pengumbang*), those very low tones would be about 30 Hz, close to the lower limit of human hearing. In that case, maintaining a constant *ombak* would put the *pengisep* partner at about 38 Hz—about a musical fourth higher.

Comparison of Toth Plots

Comparing individual plots is a good way of understanding the relationships among those many gamelan, spread across Bali. We can discern general tendencies, and explore specific idiosyncrasies or anomalies. Figure 11 shows the graphic results of generating Toth Plots for all 49 gamelan measured in the mid-1970s, as well as five new measurements from October 2019. As mentioned above, these five gamelan were deliberately chosen from Toth's original set, to offer a small sample of historical change in tunings across about 45 years.

Overview and Musical Implications

What features do these plots show? First, from a global perspective, they reveal a hitherto undescribed degree of complexity of tunings in Bali. The fact that gamelan tunings differ from one another in overall pitch height, precise interval profile, and octave treatment has been pointed out by other researchers. These plots reveal at a glance that note-to-note divergences in octave treatment within a single gamelan's tuning are, in fact, also common, and found in gamelan sets across the island. The musical consequences of this variability are noteworthy. If the 25 or so musicians of a *gamelan gong kebyar* tuned in this way were to play simple unisons (with doublings across two, three, or four octaves), up and down the scale, we would notice differing qualities of sound from one note to the next. Subjectively, one scale degree might sound more pungent or acidic, owing to a large degree of compression of stretching of its octaves; while the neighboring one is less so, perhaps sweeter in quality, or differing in some other, difficult-to-verbalize way.

But music in Bali is rarely played in simple unisons. Usually, some parts are active (at a faster metric level, i.e., more subdivided rhythmically) while others move relatively slowly or are momentarily static, generally following, in traditional music, the stratification from low to high, slower to faster. The instrumental groups are further differentiated by timbre. The layering of music on many levels—instrumentation, metric level, dynamics, and other inter-part relations—means that particular aspects of these tuning differentials are revealed at particular moments. Musical function plays a role: The *ugal* and *trompong* players are more soloistic and have higher degrees of improvisatory freedom than others to interpret a melody. For that reason, facets of the tuning system, such as the precise tuning of a scale degree in one register, or the rate of second-order beating of an octave, might come to the fore in these instruments at particular moments. These subtleties sometimes emerge melodically, and sometimes vertically.[14] A certain tone might take on a special character in certain melodic contexts. While the full gamut of instruments and frequencies of a gamelan might be easy to show in a table or Toth Plot, actual music has infinitely variable shapes, textures, shades, and nuances of instrumental balance, all of which interact with, and can take advantage of, these tuning intricacies.

14. In fact, gamelan tuners will often play a melody in one register, listening carefully to the sequential intervals, and adjust a note based on these purely horizontal considerations, without necessarily checking—or at least, not being primarily guided by—the vertical (octave) relationships.

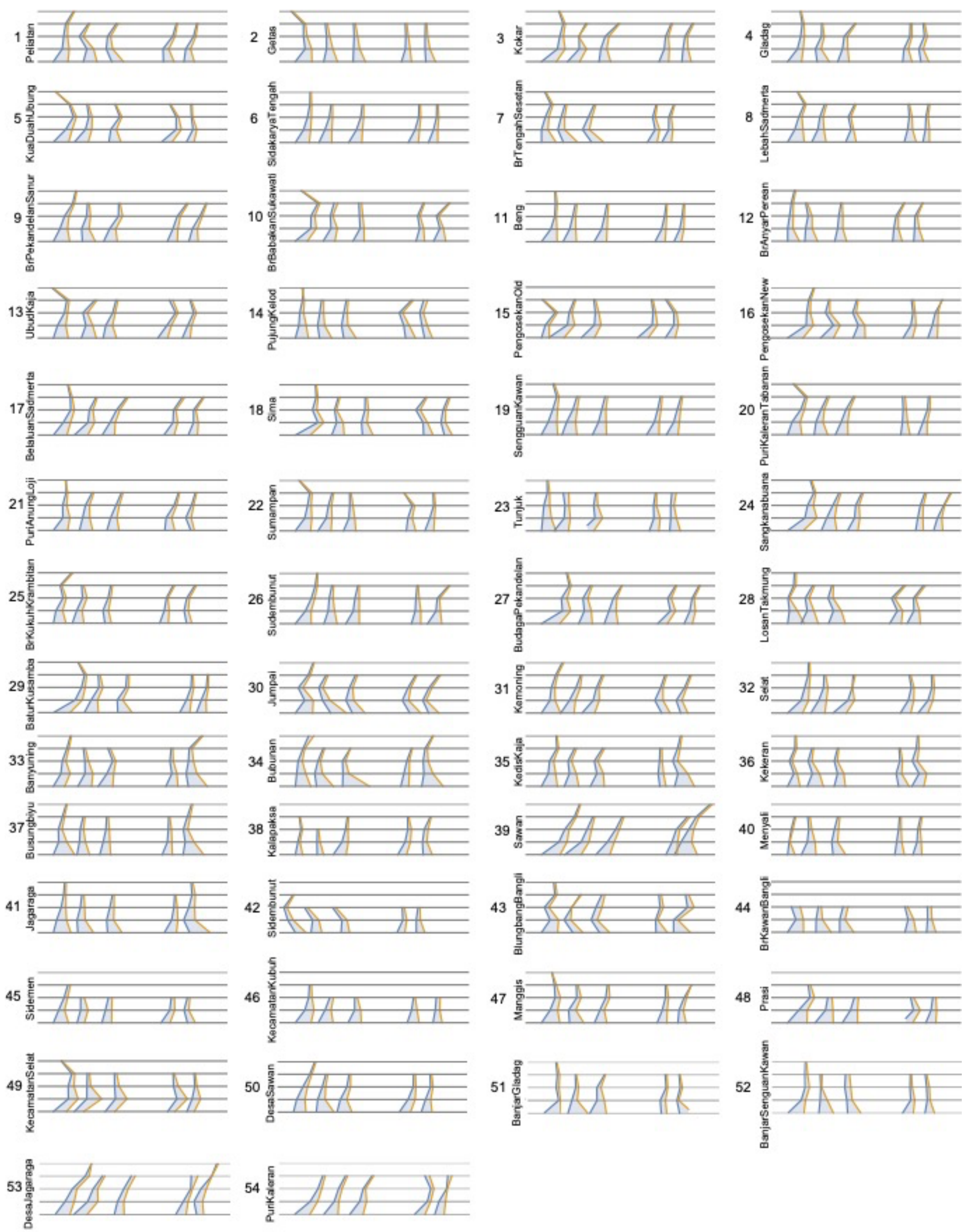

Figure 11. Toth Plots for 54 *gamelan gong kebyar*—49 from Toth's data, and five measured in 2019. The axes are identical to the example in Figure 9. All plots are normalized so that the leftmost blue point in the lowest octave, the lowest *ding*, is the reference for 0 cents.

Features, Tendencies, Outliers

Zooming in a step closer, we can start to compare the Toth plots and see various features or characteristics shared by several. Individually, some are more consistently tuned than most, readily visible as five spikes of very similar shape or tilt. In this category are octave tempering strategies that approach idealized templates, as shown in Figure 16. Others, as discussed below in "Octave Treatment: Variation by Register," require statistical analysis to reveal more subtle resemblances or tendencies, and explanations from gamelan tuners about why they exist.

Other recurring traits raise questions not easy to answer. For example, the highest tone of a *gong kebyar*, *ding*, which appears only on the *kantilan*, is often exceptionally flat—something that the author (Vitale) has experienced in his own practice. This manifests as a sharply left leaning tip of the *ding* spike, visible in Toth plots 2, 7, 8, 10, 13, 20, 22, and 49. There are many possible explanations. It may occur because it is difficult to hear such high pitches clearly. It may occur as a consequence of the short, thick shape of those keys. It may be a consequence of the forging process.

The plots also reveal true outliers, visible at a glance. Some are simply isolated instances of out-of-tune notes (or errant measurements), such as the very flat *dung pengumbang* in the highest register of no. 53. But there are also intriguing exceptions, such as the super-stretched octaves of Sawan in its 1975 tuning (no. 39), especially when compared to our re-measurement of Sawan's tuning in 2019 (no. 50). This is explored below in the section on historical changes in tuning.

Reductive Visualization

Another challenge to common assumptions about tuning arises from a basic question: What is "the" tuning of a gamelan, in terms of visual and numerical reduction? Historically, almost all researchers (including, as we shall see shortly, Toth himself, for certain purposes) have reduced the tuning of a gamelan into a one-octave span of precise frequencies, such as shown in Figure 12.

This type of graphic has certain advantages. It offers an immediate visual sense of the proportionate distances between the intervals. It is clear, precise, based on actual data measurement, and simple to reproduce on an adjustable-pitch instrument—that is, for those accustomed to representing tunings visually, which might not be true for most *pande* or musicians in Bali.[15] The choice of the third octave is, however, not only an outsider's perspective. Gong smiths and tuners also regard this one-octave span as central. In the tuning process, this is where they start, on a single *pemade*, to (in Toth's words) "lay the bearings" (Toth 1980). Once set, this single octave becomes the guide as they work outwards to higher

15. We make no assumptions, but note that the use of modern technology is changing perceptions of audio visualization in Bali. See, for example, McGraw 2008.

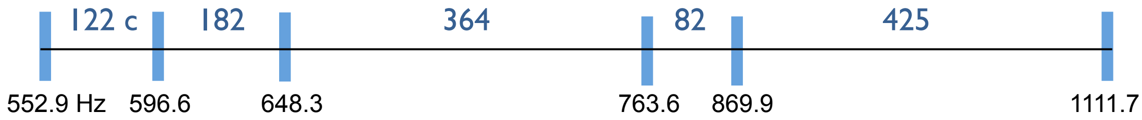

Figure 12. A representation of the tuning of the gamelan of Gladag (Badung regency), drawn from Toth's data set, using the third octave only, and means (averages) of the *pengumbang* frequencies. Note that the lower numbers represent frequencies in Hz, while the upper ones show intervals in cents.

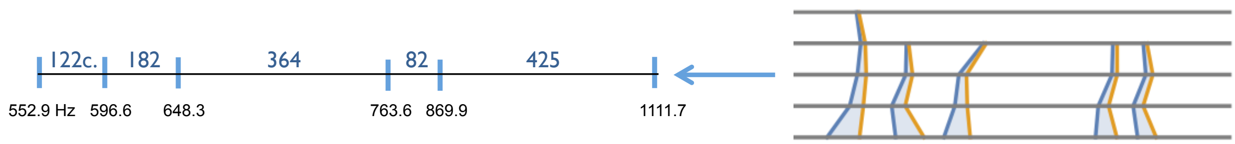

Figure 13. Toward a more comprehensive visualization: The tuning of Gong Gladag in two forms. On the left, we see the single-octave span of intervals as used by many past researchers, showing only *pengumbang* frequencies and intervals within a single octave. On the right is the Toth plot for this gamelan, showing octave treatment for the entire four-octave range of the orchestra. The arrow clarifies the relationship between the two.

and lower octaves and to the partner instruments.[16] Likewise, while most gongsmiths keep sets of 21 *petuding* (tuned bamboo sticks) to archive a tuning and later re-create it, sometimes a set of five is considered sufficient to capture it. Such a reduction does, in other words, embody the primary features of the tuning, at least as a starting point or a shorthand for comparison (as we shall see with the *begbeg-tirus* issue below).

On the other hand, the overall complexity of sonic relationships revealed in the Toth Plots clearly does matter in musical realization, and the octave-by-octave differences relate directly to the "shorthand" version: Variable octave treatment from note to note means that the intervals shown in Figure 12 would be different if we had chosen a different octave of that gamelan—for example, the second rather than third from the lowest. For that reason, and the many acoustic intricacies of real-life music as touched on above, we suggest that any comprehensive visualization of a gamelan's tuning should include both types, side by side, as shown in Figure 13, and indicate which octave is designated in the single-line reduction.

Octave Tempering Strategies

We adopt here our formalization (Vitale and Sethares, 2020), which treats octaves in a way that can be considered *tempering,* analogous to the way, in Western music, modifications or compromises are made in certain intervals to address intervallic relationships and constraints. Five possible strategies, interrelated through a *tempering parameter t*, are:

16. The author (Vitale) can attest to the practical usefulness of this approach from years of experience tuning gamelan. The third octave of the *pemade* is easy to hear, is doubled by the most instruments, carries the primary melodic elaborations, and provides a central, easily referenced starting place.

(i) t=-1 the *pengumbang* is moderately compressed; the *pengisep* is highly compressed

(ii) t=0 the *pengumbang* is tuned to a perfect 2:1 octave; the *pengisep* is compressed

(iii) t=1/2 the *pengumbang* and *pengisep* "split the difference," so that their mean values show 2:1 octaves

(iv) t=1 the *pengisep* is tuned to a 2:1; the *pengumbang* is stretched

(v) t=2 the *pengumbang* is highly stretched; the *pengisep* is moderately stretched

These idealized octave strategies are shown in Figure 14.[17]

Such idealizations reveal templates that may have been used by at least some smiths and gamelan tuners in their work, as noted by Toth and one author (Vitale, through tuning, research, and interviews with tuners.) Looking at the gamut of tuning data shows some patterns. Focusing on individual scale degrees, it is clear that particular octave-tempering strategies are often applied. An example is shown in Figure 15, where four of the five notes show shapes plausibly close to the idealized tempering strategies. This emphasizes that a variety of such templates may occur in the different notes of the same gamelan.

There are a few gamelan sets that appear to use a consistent tempering strategy for all the scale degrees. Figure 16 shows three gamelan tunings that closely approximate tempering strategy (iv), with *pengisep* octaves approaching a 2:1 ratio (as shown by the almost vertical orange lines), and correspondingly stretched *pengumbang* octaves.

One strategy consistently applied is, however, the exception. Most of the Toth plots of Figure 11 appear to apply mixed octave strategies with substantial note-to-note variation, usually deviating from any of the idealized shapes of Figure 14. For example, Gong Sawan (No. 39)

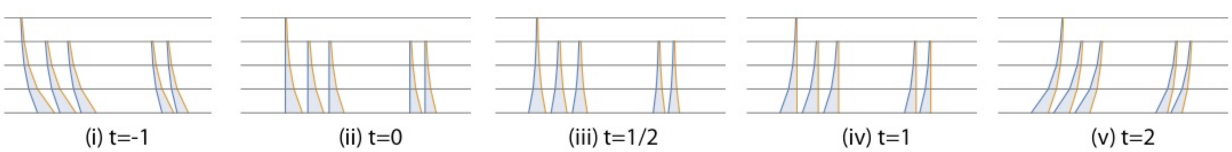

Figure 14. Five idealized octave-tempering strategies, assuming a constant ombak. Each of the five horizontal axes shows cents. Vertical lines indicate 2:1 octaves (1200 cents). The vertical axis is (log) frequency where the interval between each pair of lines is an octave. Thus, the low instruments such as *jegogan* are found at the bottom, and the highest, the *kantilan*, are at the top.

17. One principle that can be seen visually is that the octaves of the *pengumbang* (blue lines) are always wider than the octaves of the *pengisep* (orange lines). If the *pengisep* octave is stretched, the *pengumbang* octave is even more stretched; if the *pengumbang* octave is compressed, the *pengisep* octave is more compressed. And while it is common for the *pengumbang* octave to be stretched while the *pengisep* octave is compressed, the opposite (with the *pengumbang* octave compressed and the *pengisep* stretched) is not possible.

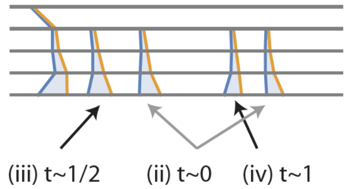

Figure 15. Toth plot for the gamelan of Getas (Gianyar) shows octave strategy (ii) used for the scale degrees *deng* and *dang*. The *pengumbang* octaves are close to 2:1, and the *pengisep* octaves are compressed as indicated by a leftward-leaning orange line. Similarly, *dong* is approximately strategy (iii), while dung approximates strategy (iv).

Figure 16. Toth plots of three gamelan, from three different regencies of Bali, reveal a consistent use of octave tempering strategy (iv), with *pengisep* octaves close to 2:1, and *pengumbang* octaves stretched. These tunings are numbers 6, 11, and 19 in the data set.

shows hyper-stretched octaves that do not conform to any of the five strategies.

What commonalities or tendencies do the data show? Is there an overall tendency in octave treatment, for example, that is not immediately visible but discoverable in the data? One way to explore this question is to calculate the tempering parameter for each gamelan as a whole, by solving the optimization problem given in Equation (9) of Vitale and Sethares (2020). Next, we consider whether the tempering parameter data show *geographic* variation, which, if found, would be one aspect of regional style in Balinese tuning practices. Such differences by regency *(kabupaten)* were one of Toth's concerns; his conversations with many tuners made it clear that aspects of tuning are regarded as another aspect of regional identity in gamelan performance practice, along with musical style, pride, prominence or fame of particular ensembles, and more (Toth 1993). As a first step, we calculate the t values for each gamelan, as above, to find the mean and standard deviation for each district, and plot the distributions in standardized curves representing the mean and variance. The results are shown in Figure 17. Observe that the three tall peaks (corresponding to districts Karangasem, Tabanan, and Klungkung) have significant area without overlap, suggesting that the gamelan in those three regions may indeed employ somewhat distinct octave tempering strategies. For example, almost all gamelan in Gianyar are tuned with tempering values of t less than 1 (indicating greater use of tempering strategies (i), (ii) and (iii)), while Klungkung has values of t primarily greater than 1 (indicating greater use of tempering strategies (iv) and (v)). In contrast, the gamelan from the remaining four districts overlap significantly and are spread much wider, suggesting that there is little differentiation in tempering strategy among them.

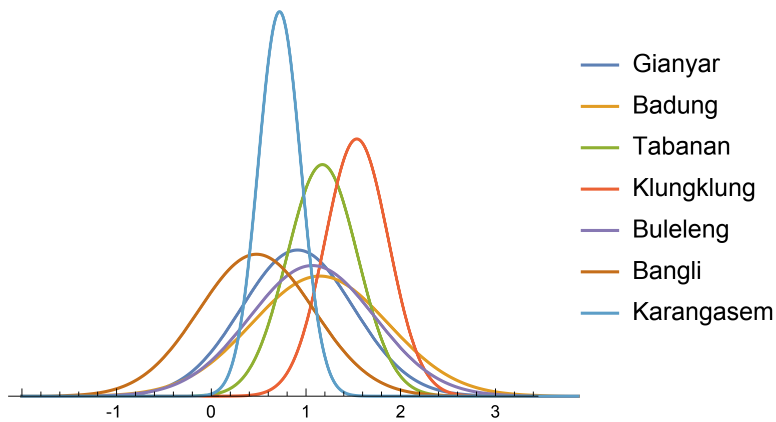

Figure 17. The tempering parameter, *t*, varies by district, suggesting regional variation in the way gamelan tuners approach the tuning of octaves. A noticeable difference is seen comparing Karangasem, Tabanan, and Klungkung, with successively higher *t*.

Octave Treatment: Variation by Register

Clearly, octave treatment in *gamelan gong kebyar* is complex. Various strategies may be used, all of which are consequences of utilizing a constant *ombak*. The *pengumbang* and *pengisep* are "bent" in one direction or another (stretched or compressed), and are interdependent. The tempering parameter reduces this bending into a single value, which, in limited ways, varies geographically.

But a single tempering parameter for an entire gamelan tuning is highly reductive, and oversimplifies the situation. Both the Toth plots presented in Figure 11, and discussions with gamelan tuners by Toth and the author (Vitale), reveal another way to treat octaves throughout the range of the gamelan. Just as it is common to bend the octaves differently from one scale degree to another, it appears that *octaves are treated differently by register*. Toth (1980) notes that one common strategy is to use "stretched octaves from the first to the second octave, near-perfect from the second to the third, and again stretched from the third to the fourth." He reports that, according to tuners and musicians, the goal is to prevent the lowest and highest registers from being "covered" by the others and hence (relatively) inaudible. In other words, functional aspects of orchestration—especially the fact that the skeletal melodies, carried in the lower registers, should be prominent in the orchestral texture—are addressed through octave tuning strategies. Toth (1993, 106) writes (translation Vitale):

> The profile (type) of multi-octave treatment most widely seen for the *pengumbang* instruments uses stretched octaves from the third to the fourth octave; octaves that approach perfect (1200 cents) from the fourth to fifth octave; and again, stretched octaves for the fifth to sixth octaves. The pattern of octaves "bends" at the extremes—at the bottom and top ends. *[Note: Toth's labeling of octaves differs from ours: his third-to-fourth octave corresponds to our first-to-second.]*

This strategy for octave treatment corresponds to a "U-shape" that has been described to the author (Vitale) by smiths and tuners.[18] However this is somewhat difficult to see by visual comparison because of the way Toth plots represent the degree of stretch in the slope of the lines in the spikes, and the wide variability in the data. For that reason, we utilize a different data visualization, plotting the *relative amount of stretch* in each of the octaves for each scale tone separately. This results in four possibilities:

"U" shape more stretched – less stretched – more stretched

Inverted "U" less stretched – more stretched – less stretched

Slash "/" less stretched – more stretched – even more stretched

Backslash "\" more stretched – less stretched – even less stretched

Figure 18 shows all the octaves of each note in the scale for the gamelan of Peliatan. In this tuning, the four octaves of *ding*, as well as the three octaves of *dong*, show the "U" shape, while the other scale steps have different shapes. The same information is also present in the Toth plot of Figure 10, though somewhat more difficult to see. The "S" contours of the spikes for *ding* and *dong* in the Toth plot correspond to the "U" shapes on the left side. Similarly, the slightly crooked backwards (flipped left-right) "S" contour of the *dung* and *dang* spikes corresponds to the inverted "U" shape.

All four of the octave shape curves regularly appear in Toth's data. Classifying the shapes of all octaves of all the notes in all the gamelan in the data set reveals 98 "U" shapes, 51 inverted "U", 29 slashes "/" and 67 backslashes "\".[19] This confirms a greater preference for the "U" shape that Toth reported, despite the considerable variation among the gamelan. On the

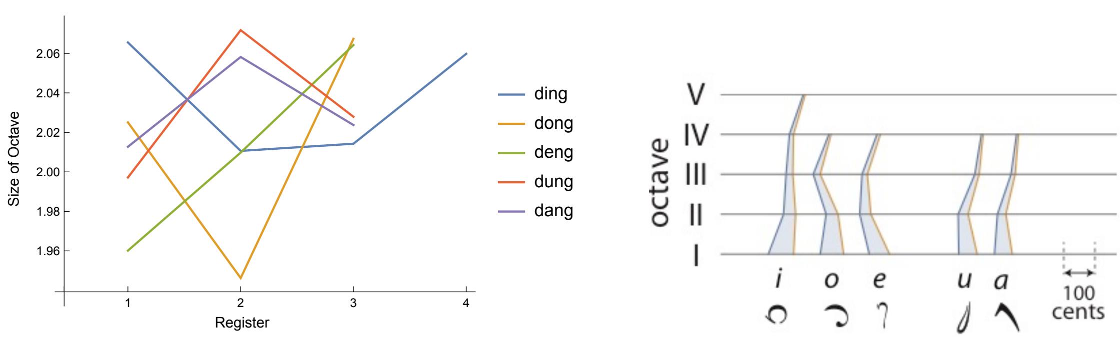

Figure 18. The multi-octave change for each scale tone is shown for the Gamelan of Peliatan. Three of the four common shapes occur in this gamelan: *ding* and *dong* show the U-shape, *dung* and *dang* show the inverted U, and *deng* is the "forward slash" shape (/).

18. Pande Sukerta and Wayan Suweca have both described this "U" shape via hand gestures (personal comm.) It is important to note that Sukerta (a gamelan maker) and Suweca (a famed musician and gamelan tuner) may have been the same experts who conveyed information to Toth, which he in turn mentioned in the quote.
19. There are several gamelan in the set which do not contain all octaves (e.g., see Toth plot no. 44, for the gamelan of Br. Kawan, Bangli, and no. 48 for Prasi, Karangasem). When there are fewer than three octaves—that is, only two points—the U and inverted-U degenerate to / and \. We removed these from consideration.

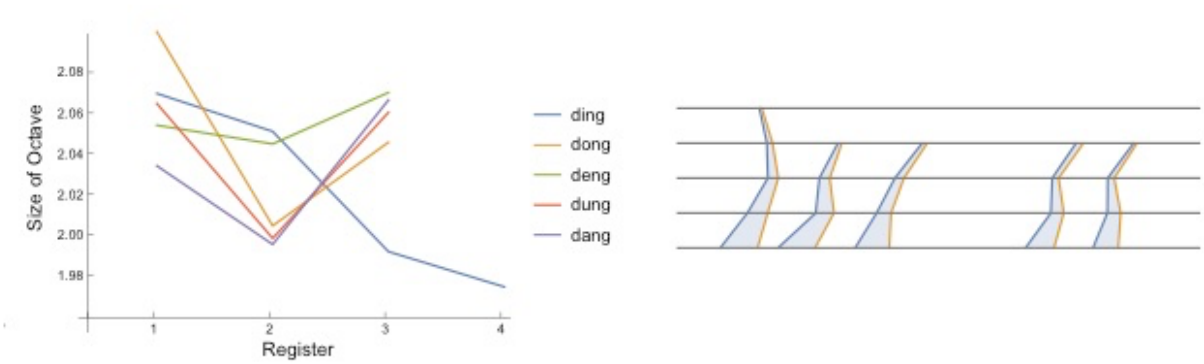

Figure 19. Multi-octave change in the five scale degrees of Belaluan Sadmerta. On the left, we plot the amount of stretch of the octaves. For this gamelan, four of the five scale tones show the U shape, while only ding shows the \ shape. On the right, the Toth plot for this gamelan.

other hand, no single gamelan clearly manifests the "stretched octave – perfect octave – stretched octave" strategy for all scale steps in all octaves. An example of a gamelan that nearly meets these requirements is Belaluan Sadmerta (no. 17 in Figure 11), which is shown in Figure 19. The gamelan from Br. Losan, Takmung (no. 28) is another close fit. But, like the tempering parameter, no single strategy for octave treatment by register is used for all gamelan. We posit that the "U" shape may be an idealized template that is widely held by smiths and tuners, and is manifest as a general tendency throughout the data, but not unequivocally implemented in practice.

Another way to analyze octave treatment would be by scale tone: Is it possible that particular scale tones tend to use one or another multi-octave shape, generally speaking? For example, is *ding* on many gamelan treated more often with a "U" shape? Separating the shapes by scale tone, however, reveals no clear pattern; each has approximately the same proportion of shapes as the others. We also tried a geographic approach, to see whether these octave shapes showed statistical variation by regency. Again, no clear pattern emerged.

TUNING MODELS: *BEGBEG* VS. *TIRUS*

This section leaves the complex realm of octave treatment, and turns to one of the most basic aspects of gamelan tuning—the intervallic profiles of each gamelan, showing the relative distances between scale tones as defined in the third octave. How are these variations conceived by gamelan tuners and musicians? Do they use templates or guidelines in shaping them? Through his many conversations with *pande* and gamelan practitioners, Toth documented two scalar profiles used for *gamelan gong kebyar* tunings (1993, p.102; translation, Vitale):

> Tuners and musicians use a particular concept in discussing tuning: *begbeg* and *tirus*, as the opposing poles along a spectrum of variation for *gong kebyar* tuning. *Begbeg* (which is also sometimes called *benang)* means straight, parallel. *Tirus* means shrinking,

> converging. One tuner explained this principle with three examples of actual tunings: *Begbeg, sedang* (middle/average), and *tirus*. Twenty-one bronze keys were used to illustrate each one, from *ding* on the jegogan to the highest *ding* on the kantilan. This tuner made all the octaves equivalent at 1200 cents, that is, "pure" octaves. In Figure 2, I have illustrated each of these tuning examples within a single octave. The tuner explained, "*dang* begbeg becomes *dung* tirus." For each of the three, he started precisely on the same note [frequency] for *ding*. The *tirus* tuning has degrees on top that "stand out" [stick out]. *Tirus* is "stretched" in comparison with *begbeg*. The intervals from *deng* to *dung*, and from *dang* to *ding* above, which normally are much larger than the other intervals, are reduced (made smaller) in *tirus*. The profile of large intervals in *tirus* is reversed compared to *begbeg*.

This conception of gamelan tunings along a spectrum from *begbeg* to *tirus* has been confirmed by other gamelan tuners and musicians.[20] What is the meaning or purpose of these interval profiles? Toth reports that it had to do with musical style: *Begbeg* is best for modern, fast, angular music styles such as *kebyar*, and for accompanying the *legong* dance; *tirus* is more appropriate for older, slower repertoire, such as *lelambatan*. An intermediate or average profile, meanwhile, would be usable for both as a kind of compromise.[21] One explanation offered was that the greater contrast in interval size in *begbeg* aligned with the greater musical

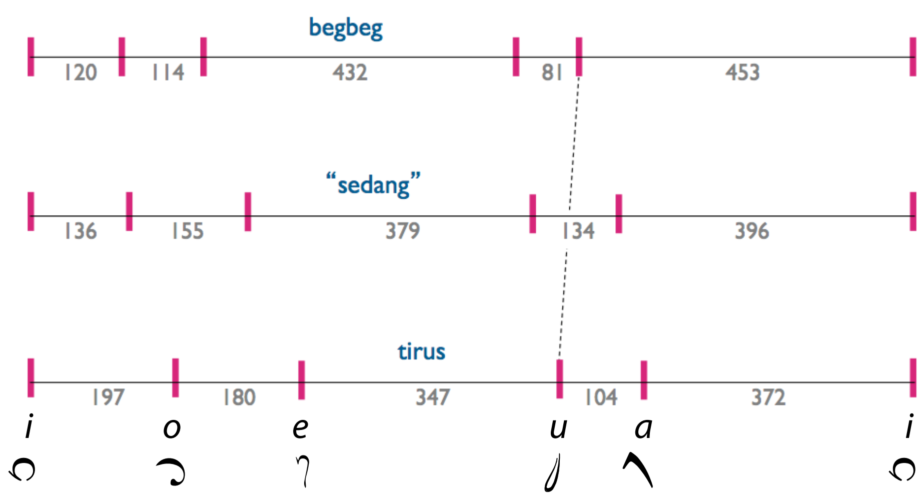

Figure 20. (Recreated from Figure 2 of Toth 1980.) The two types of interval profiles, *begbeg* and *tirus*, plus an intermediate one (*sedang*). The numbers indicate interval sizes in cents; the dotted line shows how "*Dang* begbeg becomes *dung* tirus."

20. The *begbeg-tirus* conception has been confirmed to the author (Vitale) by Pande Gableran of Blabatuh (pers. comm. 1995), I Wayan Pager (pers. comm. 1997), and Pande Sukerta (pers. comm. 1992), I Wayan Suweca (pers. comm. 2012), among others.

21. When confirming these two models, Pande Gableran (1995) also pointed out that most gamelan groups at that time did not want to limit their repertoire to either stylistic extreme since they play in many contexts, from traditional instrumental music in the temple, to new competitions on modern stages including a variety of contemporary dance styles. He claimed the general preference had turned to "average" (*sedang*) tuning, to accommodate both.

contrasts and asymmetries of modern repertoire.[22]

Figure 4 of Toth's 1993 article analyzes seven *tirus* and four *begbeg* tunings, and shows how they separate cleanly in a two-dimensional plot using MDS (multi-dimensional scaling, Kruskal 1964). This requires a way to measure the "distance" between two gamelan tunings. Toth adopts the root mean squared error between the intervals, using the third octave of the two tunings, to quantify their similarity or dissimilarity. One dimension of his plot is easily explained as a *begbeg-tirus* axis, while the other axis is harder to interpret.

In order to look at possible regional variation, we craft an explicit *begbeg-tirus* axis by considering the scales defined in Figure 20 (i.e., with values taken from Toth's Figure 2) to be standardized or idealized *begbeg* and *tirus*. We then calculate the distance between each tuning and the idealized *begbeg*, and the distance between each tuning and the idealized *tirus*, resulting in a pair of numbers that can be plotted as in Figure 21. The several gamelan identified by Toth as *tirus* (2, 6, 9, 18, 21, 27, 33, shown in green) and as *begbeg* (4, 7, 22, 28, shown in blue) demonstrate the same kind of separation as in Toth's Figure 4. The three gamelan sets shown in orange are the ones he identified as *sedang*, and unsurprisingly lie between the *begbeg* and the *tirus* clusters.

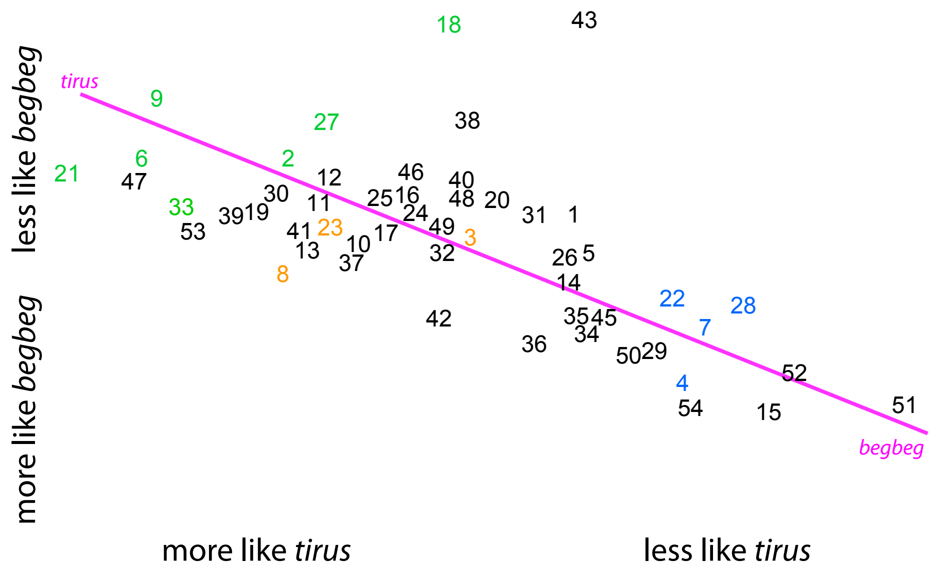

Figure 21. Distances from the ideal *begbeg* and the ideal *tirus* are calculated for all 55 gamelan, forming a continuum that ranges from "similar to the idealized *begbeg*" to "similar to the idealized *tirus*."

22. Kartawan (2014) reports that two *pande* offered a different set of impressions, with *begbeg* conveying qualities of *begah* and *wibawa* (heavy and prestigious), while *tirus* is "sweet" and "refined". However, Kartawan's focus was on *gender wayang*, in *slendro* tuning, not *gong kebyar*, and his own analysis shows that it was primarily overall tonal height that distinguished them (with *begbeg* generally lower) rather than intervallic profiles which showed only modest differences—and reversed from *begbeg-tirus* profiles in *gong kebyar*.

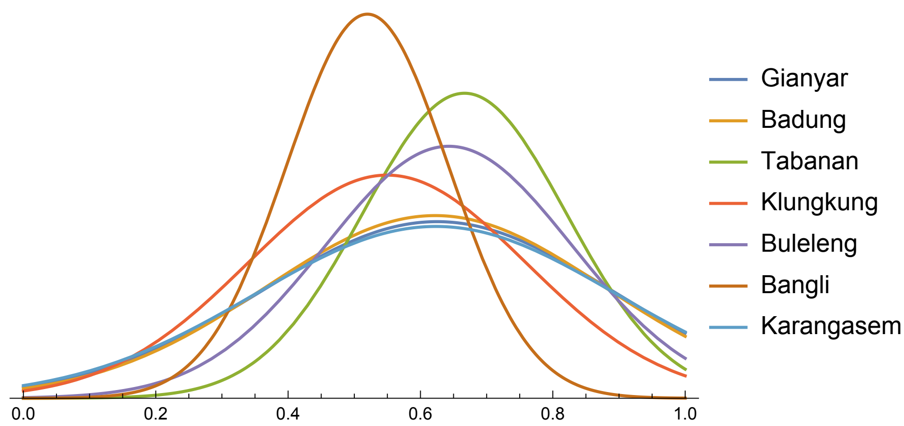

Figure 22. Distance to the *begbeg-tirus* line by district. The only exceptional district is Bangli, which is slightly shifted to the left and hence is, on average, closer to *begbeg* than the other districts.

Clearly, the bulk of the gamelan can be arrayed along the purple (best fit) line and it is straightforward to assign a single number that represents position along the line (1 = close to *tirus*, 0 = close to *begbeg*). Following a similar procedure to the previous section, we calculate the mean and standard deviation of these *begbeg-tirus* numbers for the gamelan within each district, which can be displayed as in Figure 22. Regional variation would result in distinct curves. Since the curves are mostly overlapping, there is little regional variation along the *begbeg-tirus* axis.

Nevertheless, a more localized comparison, within a single *kabupaten*, does reveal an interesting contrast. There are two distinct clusters of measurements in North Bali: numbers 34–37 (to the west) and numbers 33, 38, 39, 40, and 41 (to the east). This geographic grouping corresponds to a contrast in musical style sometimes mentioned by North Balinese musicians: *Dangin enjung*, "east of the river," and *dauh enjung,* "west of the river" (Herbst 2011).[23] And indeed, we see in Figure 21 a tight clustering of 34–36 towards the *begbeg* end of the continuum, and a tight cluster of the tunings of 33, 39, and 41 (with 38 and 40 not too distant) towards the *tirus* end of the continuum. With the exception of 37, these suggest the stylistic distinction between east and west in North Bali is reflected in the *begbeg-tirus* axis.

A Tale of Five Gamelan: Historical Changes in Tuning

The tunings numbered 50–54 in the Toth plots, measured in 2019, allow us a historical comparison. As far as we know, this is the first time that any such multi-decade changes in gamelan tuning measurements have been documented. We now look at the *begbeg-tirus* axis to see if and how they may have changed. Figure 23 is drawn exactly as Figure 21, and many features are repeated: the green numbers represent the gamelan marked by Toth as *tirus*, the

23. This refers to the large rivers flowing from the mountains to the sea, just east of the city of Singaraja, which were significant geographic demarcations in the mid-twentieth century and earlier, before modern bridges were built.

blue ones are *begbeg*, and the orange ones lie between. The five gamelan measured in 2019 are numbered 50–54 are marked in red and are connected to the same gamelan measured earlier. The change over the 45-year time period is indicated by the light gray arrows: Gamelan 50 is the same as 39 (Sawan), 51 is the same as 4 (Gladag), 52 is the same as 19 (Sengguan Kawan), 53 is the same as 41 (Jagaraga), and 54 is the same as 20 (Puri Kaleran). All show substantial shifts.

Four are now located close to the *begbeg* extreme, and the remaining one has moved towards the *tirus* side. All five of the repeat measurements, in other words, moved towards the extremes. This presents an interesting possibility: Did more recent gamelan tuners deliberately adjust tuning to be more clearly *begbeg* or more *tirus*, than those in earlier decades? Since four out of the five went substantially further towards the *begbeg* side, does it reflect the increasing predominance of modern *kebyar* repertoire over the past half-century?[24] This is possible, but difficult to say with any confidence considering the small size of this sample, without associated ethnographic research on the circumstances and intents of the groups and their tuners over this period.

Comparing the tuning data from the mid-1970s with those of 2019 reveals other changes in the life of a gamelan. Instrumentation changed considerably, and for some the range of particular instruments was adjusted. Consider the gamelan of Sawan in North Bali (shown in Figure 11 as number 39 in Toth's data and number 50 in 2019). One obvious change is that it lost its lowest note: in 1983 it was *dang*, while in 2019 the lowest was *ding*. Gong Sawan was made to conform, in other words, to the more usual layout of *jegogan* keys, with five keys

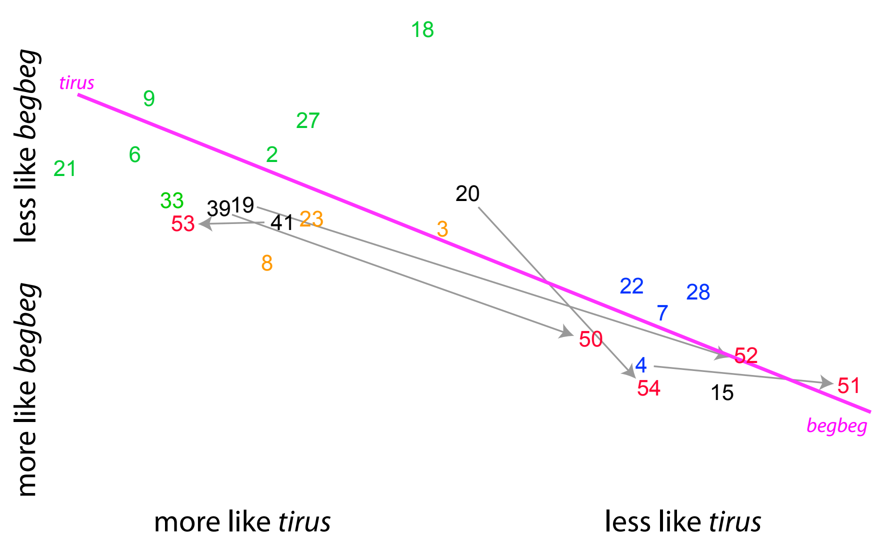

Figure 23. Remeasuring the tunings of five gamelan in the Toth set, 45 years later, reveals changes along the *begbeg-tirus* axis, as indicated by the gray arrows. Four out of the five became markedly more *begbeg*, while one became slightly more *tirus*.

24. This would go in the opposite direction suggested by Pande Gableran, who felt that the taste of most groups or owners were moving toward an averaged *sedang* tuning (see footnote 21).

rather than six. (The *jublag*, however, kept its original six keys.) Meanwhile, the remaining five *jegogan* keys were almost certainly not replaced considering how little they changed in pitch, as seen in Figure 24. There are many keys where the near-identical data suggest that the older and newer measurements correspond to the same, original keys, playing the same roles.

Perhaps the most obvious change in Gong Sawan is that the modern gamelan instrumentation has significantly expanded: 136 keys on 16 instruments plus 22 *pencon* (in 2019) as compared to 98 keys on 12 instruments plus 24 *pencon* (in the 1970s). The added ranks were two additional *pemade* and two additional *kantilan*—again, bringing the gamelan in conformity to modern standard instrumentation. The slight decrease in the number of *pencon* reflects the same thing, with the *trompong* losing two of its lowest kettles to become a standard arrangement of 10 gong kettles rather than 12.[25]

The average *ombak* of Gong Sawan also appeared to change, at first glance. In the 1975 incarnation, Sawan's average *ombak* was 9.0 +/- 3.0 Hz. By 2019, this had slowed to 8.0 +/- 0.7 Hz (see Figure 25). However, on closer examination, the larger variance of the older version is due to two mistuned notes in the highest register—the highest *dung* on the *reong* (considerably flat) and high *dang* pair of the *kantilan,* with an *ombak* of 16.2 Hz. These outliers are unlikely to

	1970s (Toth)	2019 (Wijaya)
jegogan – ding (+)	132.0	128.0
jegogan – ding (-)	123.8 Hz	122.3
giying – deng (+)	142.2	140.3
giying – deng (-)	134.4	133.6

Figure 24. Tuning measurements of a few keys of the gamelan of Sawan, Buleleng, showing their change over about 45 years. (The *giying* was labeled *ugal* in Wijaya's measurements.)

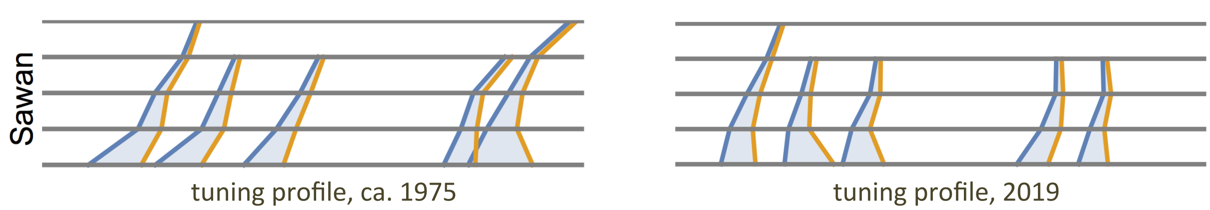

Figure 25. Historical change: On the left side, the tuning of the gamelan of Sawan in the mid-1970s (plot no. 39), compared to 2019 on the right (plot no. 50). From a condition of hyper-stretched octaves, its tuning was brought into a more typical profile – but the precise why and how, considering the extreme change, remain unclear.

25. In earlier decades, gamelan groups in North Bali sometimes used the *trompong* as a low *reong*, favoring the unique sound color of the low registers. Two additional pots on the low end, in the 1970s, made it precisely an octave-lower version of the *reong*.

be intentional. Indeed, removing just these two values from the averaging calculation yields an *ombak* of 8.6 +/- 0.4: in other words, close to the original, and more accurately tuned as reflected in the smaller variance.

We do, however, see a substantial change in Sawan's tuning in terms of octave treatment and overall shifts. Looking at the 2019 Toth plot (no. 50), we can see at a glance how much less stretched the tuning is compared to the 1975 version (no. 39).

The gamelan tuners appear to have lowered the upper registers substantially. The third octaves of the *pengumbang* (-), for example, show this clearly, with a lowering of 33–65 Hz:

	i	o	e	u	a
1975 (Hz)	539	585	650	812	873
2019: (Hz)	506	548	594	758	808
change (Hz)	-33	-37	-56	-54	-65

The next higher octaves, mostly on the *kantilan*, show this even more extremely: The pitches were lowered by as much as 224 Hz, which exceeds a whole step in 12tet:

	i	o	e	u	a
1975 (Hz)	1117	1195	1331	1691	1838
2019: (Hz)	1038	1101	1199	1521	1614
change (Hz)	-79	-94	-132	-170	-224

This is an extraordinary degree of change, and the gamelan of Sawan is tuned very differently in 2019 than it was in 1983. Why were these upper registers lowered so much? One tentative explanation is provided above, in the discussion on *begbeg* vs. *tirus*: Perhaps the later tuners wanted (or were instructed) to bring the profile closer to *begbeg*, in line with stylistic considerations. Or perhaps the tuners felt that the huge degree of octave stretching in the gamelan's tuning was excessive: Note the highly right-leaning spikes in Toth plot number 39, compared to the 2019 tuning shown in plot 50. In that case, the *begbeg-tirus* change could have been a by-product.

Another possibility presents itself, especially considering the difficulty of changing the tuning so much. (Lowering a *pemade* key by 50+ Hz, or a *kantilan* key by a whole step, requires a huge amount of filing, which risks damaging the shape and integrity of the key.) Several new instruments were added over this multi-decade time period. Perhaps the change in tuning was the result of the process of re-unifying the gamelan's tuning. It is possible that the new instruments, made at a physical distance from the gamelan, came out considerably flat—i.e., much lower than the existing ones. If so, the tuner might have sought to meet in the middle, bringing the older ones down in pitch while, presumably, raising the new ones. Such challenges arise almost any time instruments or individual keys or *pencon* are added or replaced, and tuning integration is sought. This, however, would be an extreme case. Lastly, is it possible that the keys and *pencon* of gong Sawan were completely reforged or replaced? [26] This would provide a single explanation for the multitude of changes. Sawan presents an example of the need for more research with the older members of this highly respected and long-established group and village, to discover what transpired.

The gamelan of Gladag (numbers 4 and 52) follows a similar pattern. The 2019 gamelan is greatly expanded, with 16 keyed instruments and 2 *pencon*, compared with the 1983 gamelan, which had 12 keyed instruments and 2 *pencon*. Again, the expansion involved adding two new *pemade* and two *kantilan*. In terms of tuning, we see some clear stability. The lowest *ding* pair, for example, is hardly changed: 131.8 (-) and 138.7 (+) in 1983, and 131.3 (-) and 139.5 (+) in 2019. The *ombak* in 1983 was 7.1 +/-1.3 Hz; this increased slightly in 2019 to 8.1 +/- 0.7 Hz. Most other pitches also appear to have changed little, indicating good integration of the new instruments' pitch with the existing, much older ones. Perhaps the most striking historical change is the apparent (mis)tuning of a few *pencon* in 2019. While all the *pencon* in 1983 are within a few Hz of the average *pengumbang* or *pengisep*, there are a few outliers in 2019. For example, the second octave *ding* averages 273 (-) and 280 (+), little changed since 1975, but the corresponding *trompong* pot is 255, about 25 Hz flat. Similarly, the third octave *dang* on the *reong* is, in 2019, more than 20 Hz flat from the corresponding *pengumbang* average. What accounts for this? We guess that the original pots may have cracked and were replaced in the intervening years, since detuning them in this way could not have been easy nor intentional. Aside from these differences, the Toth plots for the 1975 and 2019 Gladag measurements have fairly similar shapes. The only general change is that Gong Gladag was more out of tune in recent years, as seen in the increased non-uniformity of the spike shapes. This may be the result of inactivity and loss of prominence. In the 1970s and 80s, Gong Gladag was famous and frequently appeared in island-wide gamelan competitions, while more recently it has been relatively inactive.

The gamelan of Sengguan Kawan, Gianyar (numbers 19 and 52) also grew larger over the years and experienced some interesting tuning changes. Many of the keys are tuned higher in 2019 than in 1975: the lowest *ding* has increased from 123 (-) and 130 (+) to 128 (-) and 136 (+), the lowest *dong* has increased from 133 (-) and 140 (+) to 144 (-) and 151 (+). This trend is reflected throughout, so that the third octave *ding* in 2019 is almost indistinguishable from the third octave *dong* in 1975. In the Toth plots, the 1983 gamelan displays a consistent $t=1$ tempering. By 2019, three of the five scale degrees have changed to a spike shape more reminiscent of $t=0$. The scale, the base pitch, and the octave treatment have all changed. Again, the many changes beg the question of what the group's (and tuner's) intentions and reasoning were, and the

26. Reforging the keys and *pencon* of an entire *gamelan gong kebyar* is rare but not unknown: This also took place in the village of Pinda (Gianyar regency) in the 1990s, with a notable—and, by some local estimates, lamentable—loss of the previous, idiosyncratic, and easily identifiable Pinda tuning.

physical constraints of the instruments, if any.

The Toth plots for the gamelan of Jagaraga (numbers 41 and 53), show a true transformation in octave treatment.[27] In 1975, the spikes are mostly vertical, showing a balance between stretched and compressed octaves, and suggesting a $t=1/2$ octave tempering strategy. By 2019, all the spikes lean to the right, showing that both the *pengumbang* and *pengisep* are stretched considerably. Thus, its octaves have "traveled" in the opposite direction from the gamelan of Sawan, becoming more stretched rather than less. Visually, they are quite different. In terms of intervallic treatment, we see another movement in an opposite direction: This is the only gamelan of the five newly remeasured ones to have moved closer to the *tirus* tuning and away from the *begbeg,* as described above.

The fifth gamelan, of Puri Kaleran at Tabanan (numbers 20 and 54), increased in size from 10 keyed instruments and 3 *pencon* to 18 keyed instruments and 2 *pencon*. In 1975, the highest note was the usual *ding* (at about 2100 Hz). This key was removed or lost over the years. As with the Jagaraga tuning, the Toth plots show an increase in octave stretching over the years, with a general leaning of the spikes to the right. Unlike Jagaraga, the scale intervals have moved closer to the *begbeg* axis and away from the *tirus*.

Conclusions

Andrew Toth's work, writings, and tuning data allow us an unprecedented look at Balinese tuning systems. His work, and our extension of it, is rooted or positioned in the ethnomusicological traditions of studying Indonesian tunings, mostly by foreign researchers, using Western concepts of data, frequencies, and cents relationships. However, it is considerably more expansive than the work of other writers owing to its ethnographic dimensions and the quality and quantity of Toth's tuning data. From years of interviews and discussions with tuning practitioners, Toth brought essential aspects of Balinese *gong kebyar* tuning into written awareness. These include octave treatment, the interdependence of *ombak* and octave, and the *begbeg-tirus* tuning model. Moreover, Toth made clear how these various aspects can vary geographically by district *(kabupaten)*, and provided a large enough data set with representatives from the entire island, which enabled us to explore these variations and preferences.

One of his most effective innovations was in the realm of data visualization—what we have labeled Toth Plots in his honor. By inputting and decoding his data from archived printouts, and applying modern computer-graphic techniques, we were able to graph each of the 49 gamelan tunings in his sample into Toth plots, along with five newly commissioned

27. There were three *pencon* for which the measurements made little sense (the second octave *dang* and adjacent third octave *ding*). The 14 keyed instruments were consistently measured at 397 (-) and 402 (+). The two corresponding *pencon* had frequencies 351 and 420. Accordingly, these were removed from the data used to draw the Toth plots.

ones. These plots illuminated a feature of Balinese tuning never before noted: Octave treatment varies from note to note within a single gamelan, not only occasionally but typically. While certain tuners seem to have followed a single octave-tempering strategy comprehensively for an entire gamelan, these are exceptions. The variability from note to note has musical consequences, since facets of tuning relationships and qualities are revealed in the complex textures and orchestration of actual music. Also, this variability raises fundamental questions about how a tuning might be visually or graphically represented: It has been common in past analysis to choose a single octave (typically the third from the bottom) span of intervals to represent, as a type of shorthand, the entire gamelan's tuning, but is that "the" tuning of the gamelan? Choosing a different octave, such as the second from the bottom, would produce a different profile of proportional interval distances. For clarity we suggest a combined graphic, showing both the Toth plot and the particular one-octave reduction, side-by-side.

Another tuning strategy that Toth conveyed from Balinese *pande* and tuners, also for the first time in the scholarship of foreign researchers, was the "U" shaped concept of octave treatment, a register-by-register approach meant to highlight certain groups of instruments in the orchestral texture, or, at least, to keep them from being obscured. The "U" shape means that the highest and lowest octaves are more stretched, while the middle ones less so or close to perfect octaves. Here too, the data he gathered revealed in our analysis that this tendency exists, though in a more subtle way than the simple stretched-perfect-stretched model suggests. On the one hand, none of the gamelan showed an unequivocal stretched-perfect-stretched profile. On the other hand, by analyzing the shapes of register-by-register octave treatment, we showed that, statistically, the "U" shape, generalized as more–less–more stretched, was the most common shape.

Geographically, we discovered certain trends through statistical analysis. The tempering parameter—the overall "stretchedness" of a gamelan's tuning—represented by *t*, varied by district, suggesting regional variation in the way gamelan tuners approach the tuning of octaves. A noticeable difference is seen comparing Karangasem, Tabanan, and Klungkung, with successively higher *t*; however the other districts did not show any discernable regional tendency. Likewise, a slight preference for the *begbeg* interval profile was seen in the *kabupaten* of Bangli; the others did not show an obvious preference—though we did discover an intra-regency contrast in Buleleng, between those gamelan located "west of the river" and "east of the river." However, our newly commissioned gamelan measurements, repeating five tunings from Toth's data set 45 years later, revealed something surprising: Four of the five tunings were brought much closer to the *begbeg* side of the spectrum. We hesitate to draw any conclusions from this finding since the sample size is small, and we have no ethnographic data about intent, who the tuner(s) were, and repertoire. It may reveal an historical tuning trend driven by music-stylistic factors, it may be a byproduct of other tuning changes, or it may be a statistical fluke.

Other historical contrasts were clear from the five new measurements. The most evident was in instrumentation: The five gamelan showed significant expansion, and sometimes adjustment in range of particular instruments, to match the emerging standardization of *gamelan gong kebyar* instrumentation. The additions of new instruments, however, brought up questions about tuning, in terms of integrating them into the existing set. Older instruments are stable, since the internal crystalline structure of bronze settles down after the first couple of decades, while new instruments tend to change quickly. How did tuners deal with this? Again, it is difficult to draw any conclusions. However, in a general fashion, we saw that gamelan tuning did indeed change substantially in not only one but various features, and tuning re-integration was one possible explanation among several. Sengguan Kawan, for example, changed in interval profile, tonal height, and octave treatment. More information would be needed to understand why; in any case this contributes to the idea of a gamelan as a living entity, ushered through various life phases by its players and caretakers. There may be (and probably are) stories, changes, or events impossible to know through any analysis or conjecture about the data alone.

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APPENDIX A: THE TOTH CODES

There are hundreds of pages of measurements and data in the Toth Archives in the form of late-1970s-era tractor-fed computer printouts. The raw scans from the *gong kebyar* pages are available for download. Here, we describe how to extract meaningful information from them, by tracing our own process in decoding this information.

As can be seen in the sample page shown in Figure 1, the information is encoded in a way that makes data processing easy: Each number in the body of the table is either "0" or a 4-digit number, which is ideal for the kind of formatted data common in 1970s-style computational software. Knowing that these tables were indeed Toth's way of storing his tuning data (one text entry[28] states this explicitly), and seeing the pattern of entries, we made the relatively easy assumption that each row must represent an individual instrument in a particular gamelan. Accordingly, each four-digit number appeared to represent a single frequency of a single key or *pencon*, although not in a direct or obvious way: the numbers range from about 3000 to 9000, so they were clearly not frequency in Hz! We needed to establish how to transform each of these numbers in the (n, m) position (where n specifies the row and m specifies the column), to yield the tuning of the mth key/*pencon* of the nth instrument in known units.

For the 22 columns, aside from an initial guess as to their meaning we also had handwritten labels by Toth, as described below, which helped us figure out that they represented the full gamut of 22 scale degrees.[29] Likewise, the labels of each row—the seven-digit numbers in the leftmost column—were also of obvious importance, but required decoding, from another of Toth's printouts, to understand the various pieces of information they conveyed.

After some false starts, we were able to solve these mysteries.

(a) The first column of each page of tuning data turned out to be an ID code that describes the specific gamelan, the individual instrument, and other information. Fortunately, this code is described on pages 4 and 5 of Box 1, hand-label 2.02, 08/22/82), and is explained as follows:

> Digit #1: "genre". The possible values of genre are (1) gong (meaning *gong kebyar*), (2) semar pegulingan, (3) gender wayang, (4) angklung. (Toth measured the tunings of other gamelan types, which await further analysis.)
>
> Digits #2 and #3: The next two digits specify the gamelan. The parameter is called "SETNO" and the codes are: (01) Peliatan, (02) Getas, (03) Kokar, (04) Gladag, (05) Br Dauh Kutuh Ubung, and so forth. The ones labeled *gong kebyar* are (01) through (49) and are identical to the list of gamelan in the final page of Toth (1993).

28. See Toth Box 1 Printout 4.pdf, on page 6.

29. The gamut of a gamelan in standard instrumentation is 21 scale degrees, from *ding* (jegogan) to *ding* (kantilan); however, several gamelan in this sample set go down one step further, to *dang*; thus 22 were needed.

Digit #4 shows the instrument type, encoded: (1) jegogan, (2) calung, (3) penyacah, (4) giying, (5) pemade, (6) kantilan, (7) reyong, (8) trompong, (9) gender rambat.

Digit #5 is called "PAIRNO" (pair number?). It is mostly "1" and occasionally "2."

Digit #6 is called "SEX" and there are 50% "0" and 50% "1." This indicates *pengumbang* (=0) and *pengisep* (=1). Paired instruments are often regarded as male and female, for example, the two large gongs or two *kendang* will typically include *wadon* and *lanang*, female and male partners, low and high.

Digit #7 describes which district *(kabupaten)* in Bali the gamelan is from: (1) Badung, (2) Gianyar, (3) Tabanan, (4) Klungklung, (5) Bangli, (6) Buleleng, (7) Karangasem, (8) Jembrana.

Using this key, we can interpret the first ID at the top of the page shown in Figure 1 as follows:

1011102 : gong - Peliatan - jegogan - pair1 - pengumbang - Badung

(b) The 22 columns are labeled by hand in a few of the printouts with the code: V01, V02, V03, . . . through V22. The key to this encoding can be found in a printout (Box 1, hand-label 2.02, 08/22/82, on the 4th page which is labeled "page 2"). They refer to the 22 scale degrees of a complete *gamelan gong kebyar* as follows: V01 = dang0, V02 = ding1, V03 = dong1, V04 = deng1, V05 = dung1, V06 = dang1, V07 = ding2, V08 = dong2, . . . V22 = ding5. When not present, the scale degree could be deduced by horizontal position in the table, since 22 columns were consistently used.

(c) In each field (row, column), there is a number. It is either 0 (no key or *pencon* present) or a number such as 3674 or 5561, always with four digits. We were able to convert them to Hz using the clue on page 6 of (Box 1, hand-label 2.02, 08/22/82): *"Pitches are represented by their interval in cents from C0 (approx 16 Hz). These cent intervals can be determined easily by arithmetic operations and can be converted to frequencies in Hz."* An exact value for C0 can be calculated by assuming A4=440 Hz, and observing that the frequency of C4 is then 440*2^(-9/12). Dividing by 16 reduces (lowers) this by four octaves to reach C0, yielding C0=440*2^(-19/4)~16.3516. The conversion from the reported cents value *x* to frequency is then

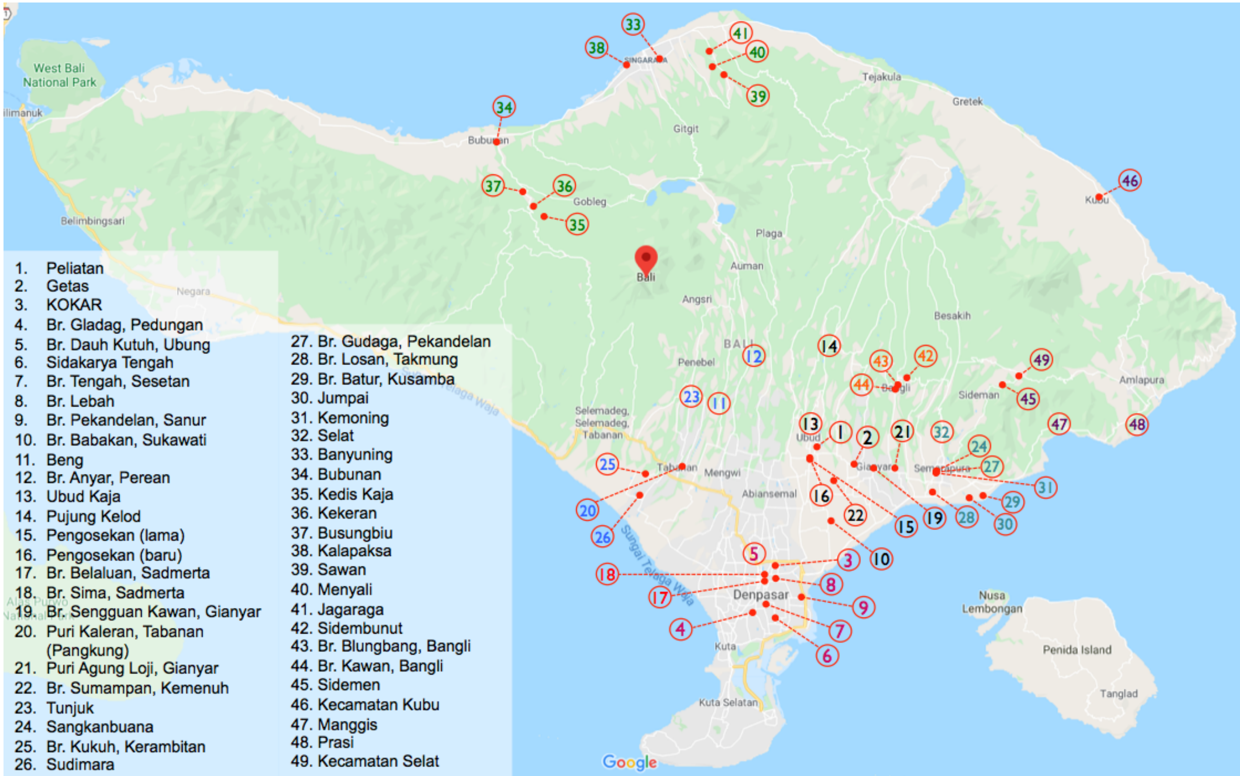
$$(\text{Freq in Hz}) = \text{C0} * 2^{(x/1200)}$$

For example, the first nonzero entry in the table of Figure 1 is 3674. Substituting this into *x* in the formula above yields 136.52 Hz.

We verified these interpretations as correct by cross-checking the numbers in the table labeled Perangkat No. 6 in Toth (1993), which lists both the four-digit codes and their translation into Hz for all the keys of gamelan Sidakarya Tengah.

APPENDIX B: THE FORTY-NINE GAMELAN MEASURED BY ANDREW TOTH

Peliatan
Getas
KOKAR
Br. Gladag, Pedungan
Br. Dauh Kutuh, Ubung
Sidakarya Tengah
Br. Tengah, Sesetan
Br. Lebah
Br. Pekandelan, Sanur
Br. Babakan, Sukawati
Beng
Br. Anyar, Perean
Ubud Kaja
Pujung Kelod
Pengosekan (lama)
Pengosekan (baru)
Br. Belaluan, Sadmerta
Br. Sima, Sadmerta
Br. Sengguan Kawan, Gianyar
Puri Kaleran, Tabanan (Pangkung)
Puri Agung Loji, Gianyar
Br. Sumampan, Kemenuh
Tunjuk
Sangkanbuana
Br. Kukuh, Kerambitan
Sudimara
Br. Gudaga, Pekandelan
Br. Losan, Takmung
Br. Batur, Kusamba
Jumpai
Kemoning
Selat
Banyuning
Bubunan
Kedis Kaja
Kekeran
Busungbiu
Kalapaksa
Sawan
Menyali
Jagaraga
Sidembunut
Br. Blungbang, Bangli
Br. Kawan, Bangli
Sidemen
Kecamatan Kubu
Manggis
Prasi
Kecamatan Selat


West Bali National Park
Singaraja
Tejakula
Gretek
Bubunan
Gitgit
Gobleg
Kubu
Belimbingsari
Plaga
Bali
Auman
Negara
Angsri
Besakih
Penebel
Amlapura
Sideman
Selemadeg, Selemadeg, Tabanan
Ubud
Tabanan
Mengwi
Gianyar
Semarapura
Abiansemal
Denpasar
Nusa Lembongan
Kuta
Penida Island
Tanglad
Kuta Selatan
1. Peliatan
2. Getas
3. KOKAR
4. Br. Gladag, Pedungan
5. Br. Dauh Kutuh, Ubung
6. Sidakarya Tengah
7. Br. Tengah, Sesetan
8. Br. Lebah
9. Br. Pekandelan, Sanur
10. Br. Babakan, Sukawati
11. Beng
12. Br. Anyar, Perean
13. Ubud Kaja
14. Pujung Kelod
15. Pengosekan (lama)
16. Pengosekan (baru)
17. Br. Belaluan, Sadmerta
18. Br. Sima, Sadmerta
19. Br. Sengguan Kawan, Gianyar
20. Puri Kaleran, Tabanan (Pangkung)
21. Puri Agung Loji, Gianyar
22. Br. Sumampan, Kemenuh
23. Tunjuk
24. Sangkanbuana
25. Br. Kukuh, Kerambitan
26. Sudimara
27. Br. Gudaga, Pekandelan
28. Br. Losan, Takmung
29. Br. Batur, Kusamba
30. Jumpai
31. Kemoning
32. Selat
33. Banyuning
34. Bubunan
35. Kedis Kaja
36. Kekeran
37. Busungbiu
38. Kalapaksa
39. Sawan
40. Menyali
41. Jagaraga
42. Sidembunut
43. Br. Blungbang, Bangli
44. Br. Kawan, Bangli
45. Sidemen
46. Kecamatan Kubu
47. Manggis
48. Prasi
49. Kecamatan Selat
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