GENERAL ARTICLE

Creative Aspects of Sonification

Oded Ben-Tal
Jonathan Berger

ABSTRACT

A goal of sonification research is the intuitive audio representation of complex, multidimensional data. The authors present two facets of this research that may provide insight into the creative process. First, they discuss aspects of categorical perception in nonverbal auditory scene analysis and propose that these characteristics are simplified models of creative engagement with sound. Second, they describe the use of sonified data in musical compositions by each of the authors and observe aspects of the creative process in the purely aesthetic use of sonified statistical data.

CREATIVE LISTENING

Recent research confirms music theorists' speculation that listening to music involves an impressive amount of mental processing [1]. These data-reductive processes facilitate interpretation by segmenting the signal and organizing the segments into numerous categories. Within a relatively brief period of time, listeners—trained and untrained alike—make judgments regarding a wide range of factors such as genre, idiom, metric inference, tonal orientation and emotional type. From these "snap" judgments, contexts are formulated and an intricate network of expectations generated [2]. While we can speculate about many of the methods listeners employ in their creative engagement with musical sound, the complexity of musical listening, particularly with the emotional associations carried with it, seems daunting.

It is, perhaps, somewhat less daunting to consider similar processes of categorical perception of acoustic signals when the listening task is purposeful, as is the case with speech perception or a nonverbal, highly specific and directed listening task such as the auditory detection of timing irregularities when tuning an automobile engine. In performing the latter task, "knocks," "rattles," "pings" and other categorized sounds allow for the detection of problems in an unseen motor. Diagnostic analysis is possible because there are a limited number of easily learned categories, making the task reasonably intuitive. Auditory analysis and interpretation of this type is, in essence, a greatly simplified instance of musical listening. The fundamental tasks—segregating intrinsic from extrinsic sound, categorizing the intrinsically relevant sounds, and integrating temporal information to arrive at an interpretation—exist in both types of listening. Our research explores the development of similarly intuitive methods and tools for categorizing and interpreting sonified data. Sonification of multidimensional data finds potential uses in scientific, industrial and medical fields.

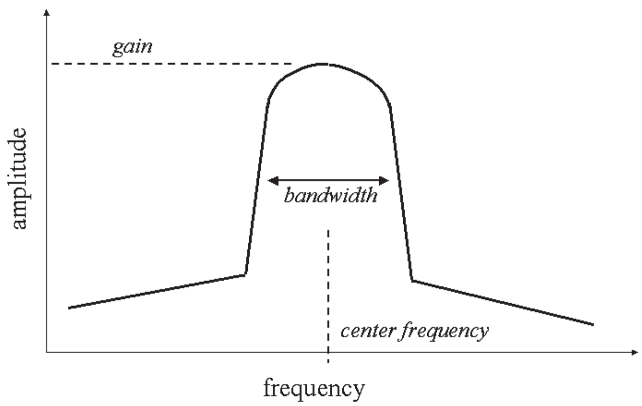
Consider, for example, one of the earliest instruments built to facilitate sonification of medical data. From the outset René Laennec's invention of the stethoscope in 1819 was meant to interpret multidimensional auditory data. Mediated auscultation with the aid of the stethoscope was, in the inventor's terms, able to interpret the integrated sounds,

> not only of the action of the heart, but of every species of sound produced by the motion of all the thoracic viscera, and, consequently, for the exploration of the respiration, the voice, the ronchus, and perhaps even the fluctuation of fluid extravasated in the pleura or the pericardium [3].

Laennec's stethoscope represented a revolution in medical diagnostics through the use of auditory information. It seems no mere coincidence that, in addition to being a physician, Laennec was an expert musician. As in the mental processing of music, categorical perception of various aspects of the acoustic signal facilitates the integration of multiple dimensions into a meaningful interpretation.

Our current work on sonification of complex multidimensional data similarly focuses on listeners' ability to track simultaneous changes in variables and integrate them into a comprehensive mental image with the aim of developing methods of auditory display that stimulate categorization processes with little training. We informally describe this aim as being "the formulation of intuitive sonification methods," and, since our model is creative music listening, we term the approach "musical sonification." In addition to the obvious potential benefits of auditory display, sonification of data provides a similar but far more constrained case of creative engagement with auditory stimuli than that of musical listening.

Fig. 1. Formant filter (© Oded Ben-Tal). A schematic formant filter. The three parameters defining the filter are center frequency, bandwidth and gain. Typical values of these parameters match specific vowel sounds.



Oded Ben-Tal (composer/researcher), Center for Computer Research in Music and Acoustics, Stanford University, Stanford, CA 94305, U.S.A. E-mail: <oded@ccrma.stanford.edu>.

Jonathan Berger (composer/researcher), Center for Computer Research in Music and Acoustics, Stanford University, Stanford, CA 94305, U.S.A. E-mail: <brg@ccrma.stanford.edu>.

We experimented with sonification of oceanographic and stock market data by using filters to create vowel-like sounds, mapping dimensions to the center frequency and bandwidth settings of individual filters anchored around a typical vowel sound. In another experiment dimensions were mapped to onset and duration.

Whether listening to the sounds of internal organs through a stethoscope, automotive engine sounds emanating from under the hood, or an audio presentation of complex data, the ability to categorize and derive meaning from non-speech sounds involves creative inference on the part of the listener.

Musical Sonification as a Scientific Tool

To be capable of offering insight, an auditory representation must be intuitive, relatively easy to learn, flexible and capable of encapsulating multiple dimensions into a single categorical perceptual event. An example of a categorical type that meets these requirements is the vowel.

In 1665 Sir Isaac Newton observed that he could identify vowel-like sounds while pouring beer into a glass. Since then considerable cognitive research has proven that humans are highly skilled at identifying vowels and categorizing timbre according to vowel matching [4].

Formant synthesis is one method in which the metaphorical use of sounds [5] (in this case the similarity between a sound and a particular vowel) can be achieved by controlling sound attributes through mapping data values to synthesis or processing parameters [6]. In the case of formant synthesis, a type of filter (called a formant filter) is used to approximate vowel sounds. By matching the parametric values of three to five formant filters to average values derived from analyzing speech, it is easy to synthesize sounds resembling different vowels. Each filter is characterized by three parameters: center frequency, bandwidth and gain; and two possible sound sources are typically filtered: white noise (non-pitched) or a pulse-train (pitched) (Fig. 1) [7].

In a previous paper [8], we explored applications of the use of formant filters to represent complex data by relying on the perceptual proximity to vowel sounds. Our approaches in these experiments involved two steps. First, we mapped data to center frequency, bandwidth and gain of a bank of filters. Second, we scaled the data such that particular states would correlate to particular vowel sounds. By "anchoring" data to a particular vowel, we hypothesized that listeners would be able to learn how to identify contexts by specifically listening for a vowel. Furthermore, the categorical boundaries that segregate perception of particular vowels could be used to create a distance metric in which relative likeness to, as well as the dynamic move toward or away from, a particular vowel could be meaningful in interpreting data and contexts.

We approach the issue from a musical perspective, noting specific features of music that address the needs of these applications. The act of listening to music involves tracking simultaneous changes in variables (such as frequency, amplitude or spectral distribution) and integrating them into a comprehensive mental image. When transferred to the realm of sonification, this dynamic assembling of mental images can be utilized in many ways—to track dynamically changing trends in an immediate and intuitive way, or to draw abstract connections between patterns distinguishing relationships that may be otherwise difficult to perceive. As in music, multiple identities and similarities can be simultaneously represented. The resulting patterns emerging from the sonic continuum need not be static themselves. Salient features enable the listener (listening to music or to data) to prioritize and attend to specific aspects of the data-intensive stream that reaches the ear, aspects that often result in a hierarchical organization. These can be used to extract structurally salient information from complex multidimensional data. Last but not least, music is (sometimes) pleasing to hear.

To interpret sonified data, listeners draw upon their powers of auditory abstraction and categorization in order to identify patterns and detect trends. In this sense, sonification involves engaged creative listening similar to the active listening demanded by music. A critical aspect of such listening is that of categorical perception, in which a continuous variation in one or more parameters yields perceptually discrete categories. This phenomenon was originally detected in speech processing but was later identified in other aspects of listening. Listeners generally classify timbre according to best-fit strategies involving abstraction and categorization that account for time and frequency domain properties. One such example is phonemic categorization in speech processing, which is often also called upon to describe non-speech timbres (as, for example, the "nasal" sound of an oboe). We thus hypothesized that vowel-like sounds could be effectively used as a basic timbral language for representing data in which similar vowels share similar data properties. In initial experiments, mapping data dimensions to the filter bandwidth and center frequency of a formant filter resulted in an auditory display in which trends and patterns could be interpreted according to the proximity of the resultant sound to any one of the cardinal vowels.

Examples of Musical Sonification

For test data sets, we used oceanographic measurements from the Mediterranean Sea [9] showing temperature and salinity at varying depths of up to 100 meters in five locations. We mapped the temperature and salinity values onto the frequency and bandwidth of formant filters such that the average of the data corresponded to the typical value for a vowel. Sequential changes to filter frequency and bandwidth over time corresponded to increasing depth. We used both a continuous sonification and discrete bursts, with the latter proving more effective. Using this basic mapping, we could hear similarities and differences between the data from the five different locations and could also identify instances of atypical behavior. The sonic patterns we produced also proved relatively easy to remember, in a way similar to recalling a melody from a song. This sonification of data is quite unlike a jagged line in a graph, whose details are very difficult to memorize.

We applied similar sonification methods to stock market data. Two important variables of stock trade are the price of a stock and the volume of trade. In one approach we mapped these two variables to the center frequency and bandwidth settings of the filters anchored around a typical vowel sound. This resulted in changes in the inflection of the vowel if the range chosen was relatively small or, if we chose larger ranges, a shift between contrasting vowels. In a separate experiment we mapped the variables to timing information: price was indicated by the number of attacks in a given time, while volume was represented by the duration of each attack. Thus, in addition to experimenting with timbral categorization, we relied upon temporal abstraction and grouping that, like timbre classification, is an inherent aspect of musical listening (Fig. 2).

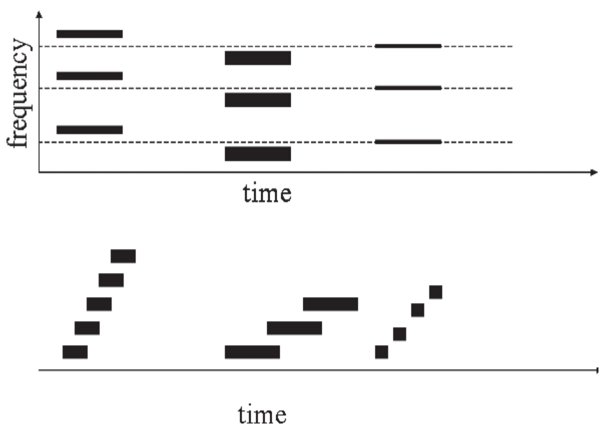


Fig. 2. Two ways of sonifying 3 days of stock trading. At the top, price and volume of trade were mapped to center frequency and bandwidth of filters. Dashed lines represent typical vowel sounds (i.e. "A") used as an anchor. At the bottom, price and volume (for the same 3 days) are mapped to onset time and duration of short sound bursts within a predefined time scope. (© Oded Ben-Tal).

Summary of Creative Processing in Listening to Sonification

Auditory display of highly dimensional data, particularly when a time series is involved, is a potentially useful tool for representing scientific, medical or industrial data sets that are unwieldy or not conducive to effective visualization. Effective sonification must complement or supplant visual display and be relatively intuitive to interpret. The temporal nature of sound makes sonification of time-oriented data particularly useful in revealing recurrent patterns and trends. Sonification can facilitate pattern detection in temporal information that occurs over varying periods of time, for example, seismic [10], astronomical or meteorological data [11].

Categorical perception is a vital component of auditory scene analysis. The segmentation and association of abstract sounds to identify phonemes is one example of auditory perceptual categorization. The universal importance of human recognition of spoken language apparently accords special significance to phonemic associations and makes the creative association of abstract sounds with phonemes an inherent aspect of listening. This observation suggests that tapping this particular aspect of "creative listening" for purposes of representing complex data may prove promising as a general approach of sonification.

Implicit in these observations is the notion that auditory display demands creative processing that is similar or identical to that of musical listening. In the second part of this paper we describe a perhaps perverse extension of these observations in which the authors forgo the meaning of sonified data and instead use sonification expressly as compositional material, bringing the inherent creativity of auditory abstractions back into the world of music.

Compositional Uses of Musical Sonification

In this section we describe the use of the previously described data and sonification methods in musical compositions.

Ben-Tal: Tangents

Both sonification methods described above (by filter settings and by timing information) are highly dependent on the specific values used and on minimizing changes in other variables—thus focusing the listener's attention on the data-loaded variables. By using very different values, I used these same methods in composition, masking their representational aspect. Sonification through formant filter settings uses short, evenly spaced, noise bursts. I was able to generate a rich and varied texture of sound by applying the same settings to other sound sources (such as recorded musical instruments) and by using much longer durations for each. Likewise with the timing-based sonification: short similar bursts were replaced with much longer (thus overlapping) sounds, with varying envelopes and filter variables. Creating different timbres in place of unified sound bursts results in a seemingly organic musical fabric. Thus timbral groupings override the representational groupings and allow for a more complex musical pattern to emerge. In both cases, selecting portions of the data allows for control of the complex trajectory of the music. Since stock data fluctuates considerably on the local level but often exhibits trends on a larger scale, it can be mined to provide a virtually endless repertoire of interesting contours.

Another method used compositionally was an extension of the time-based representation to granular synthesis. In granular synthesis a sound source is chopped into small "grains," which are then recombined to produce a different sound. In addition to the choice of sound source, the end results depend on many variables, including grain size and density, the starting point where the grain was extracted from the source, and the sampling rate at which the grain is read. Each parameter can be controlled dynamically when producing a sound. I created a variety of sound materials by mapping stock market data—this time including highest and lowest daily prices, volume of trade and closing price—to these four granular synthesis variables.

Berger: *Haiku*

Haiku, for trombone and electronics (2002) represents another purely musical application of the sonified data methods described in this paper (although in this case using a data set not described here).

Haiku is based upon the 5:7:5 proportions of the haiku poetry form. These proportions permeate the work's temporal and pitch worlds. The trombone is subjected to real-time signal processing and accompanies a prepared soundtrack played on a compact disc. The soundtrack uses solar activity data collected by the Michelson Doppler Imager (MDI) mounted on the SOHO spacecraft that is circling the sun over a million miles from Earth. Unlike the other examples, in which numerical data was mapped to musical parameter, the solar data was taken "as is," down-sampled into the audio range, filtered to remove instrument noise, and directly sent to digital-analog converters. The direct audio representation of solar activity by Alexander Kosovich—a research scientist at Stanford University's Solar Oscillations Investigation group, was used as source material for *Haiku*. I used convolution and formant resonators to shape the sound and emphasize the pulsations of the detected solar flares. Although the sonification has no immediately apparent intrinsic scientific value, the processing emphasized the temporal 5:7:5 ratio that subsequently inspired the compositional goal of abstracting the formal proportions of haiku.

Summary and Conclusions

Our line of work reveals interesting glimpses of creative processes. We propose that listening, in itself, is a creative process, in that, by identifying patterns and detecting trends, a meaningful mental image is elicited from a stream of air pressure changes. The facilities to create abstractions and categorical perceptions are critical aspects of listening, whether to speech, music or sonified data. Thus, effective sonification demands understanding something about the pattern detection and categorization processes of the listener, a topic of interest to both researchers and composers. Sonification offers a useful domain for considering creative processing on the part of listeners because of:

- the use of complex sounds: the stimuli are relatively simple but not as sonically impoverished as the simple sine-tones commonly used in listening experiments.
- purposefulness: listeners have a relatively well-defined task of extracting meaningful interpretation of data as opposed to the more vague task of appreciating music on its own terms.

It follows that data sonification offers a restricted case of listening with a somewhat controlled context in which abstraction and categorical perception can be easily assessed in terms of a listener's ability to interpret the output. In this sense we view listening to sonified data as related to listening to music (but with less "cultural baggage").

Another aspect of evaluating creativity is the interaction between research and composition activities. Music and musical ideas served as a starting point for our search for sonification methods, which in turn were reapplied to composition. The latter is especially interesting as it allows a glimpse at the sources of inspiration. For both authors the starting point was a sonic impression. There was by no means a single moment of "revelation" or inexplicable "inspiration," but rather a series of compositional decisions that resulted from a conscious and protracted process of experimenting with auditory data display in searching for effective sonification.

Sound Examples

Sound examples of the sonification techniques and the compositions discussed in this paper are available online at <http://ccrma-www.stanford.edu/groups/soni/creative-sonification.html>.

References and Notes

1. Lawrence M. Parsons, "Exploring the Functional Neuroanatomy of Music Performance, Perception, and Composition," *Annals of the New York Academy of Sciences* **930** (2001) pp. 211–231.

2. For a historical-aesthetic perspective on listening to music, see Nicholas Cook, *Music, Imagination and Culture* (Oxford, U.K.: Oxford Univ. Press, 1990), especially Chapter 1. For a discussion of auditory cognition, see Albert S. Bregman, *Auditory Scene Analysis* (Cambridge, MA: MIT Press, 1990), especially Chapter 6.

3. René Théophile Hyacinthe Laennec, *A Treatise on the Disease of the Chest*, John Forbes, trans. (New York: Hafner, 1962) p. 41. (Originally published in 1821 by Underwood in London.)

4. For a comprehensive review, see Winnifred Strange, "Evolving Theories of Vowel Perception," *Journal of the Acoustical Society of America* **85** (1989) pp. 2081–2087.

5. Bruce N. Walker and A. Ehrenstein, "Congruency Effects with Dynamic Auditory Stimuli: Design Implications," in *Proceedings of the Fourth International Conference on Auditory Display* (Palo Alto, CA: ICAD, 1997).

6. G. Kramer, "Some Organizing Principles for Representing Data with Sound," in G. Kramer, ed., *Auditory Display: Sonification, Audification and Auditory Interfaces, SFI Studies in the Sciences of Complexity, Proceedings Volume XVIII* (Reading, MA: Addison-Wesley, 1994) pp. 197–202.

7. For a review of formant synthesis methods, see Thomas Styger and E. Keller, "Formant Synthesis," in E. Keller, ed., *Fundamentals of Speech Synthesis and Speech Recognition: Basic Concepts, State of the Art and Future Challenges* (Chichester, NY: John Wiley, 1994) pp. 109–131.

8. Oded Ben-Tal, M. Daniels and J. Berger, "De Natura Sonoris: Sonification of Complex Data," in D. Attellis et al., eds., *Mathematics and Simulation with Biological, Economical and Musioacoustical Applications Mathematics and Computers in Science and Engineering* (Athens, Greece: WSES Press, 2001) p. 330.

9. The oceanographic measurements were provided by Artur Hecht, Israel Oceanographic and Limnological Research.

10. Seiji Adachi, H. Yasukawa, I. Takumi and M. Hata, "Signal Processing and Sonification of Seismic Electromagnetic Radiation in the ELF Band," *Institute of Electronics, Information, and Communications Engineers Transactions on Fundamentals of Electronics* **Vol. E-84A**, No. 4 (April 2001).

11. John H. Flowers, L.E. Whitwer, D. Grafel and C. Kotan, "Sonification of Daily Weather Records: Issues of Perception, Attention, and Memory in Design Choices," in Proceedings of the 2001 International Conference on Auditory Display (Espoo, Finland: ICAD, 2001) pp. 222–226.

Manuscript received 23 January 2003.

Oded Ben-Tal studied music and physics in Jerusalem and received his doctorate in composition from Stanford University. His music, both electronic and acoustic, has been performed in numerous countries, including Denmark, France, U.S.A., Israel and Korea, as well as various international forums such as Musica Nova - Sofia, the Dartington Festival and the Domaine Forget Festival. Currently Oded lives in London with his partner and their cat.

Jonathan Berger teaches composition and music theory at Stanford University. His recent commissions include Doubles, *a string quartet in five moments, and* Music for the Dedication of the Clark Center, *which uses sonification of hyperspectral medical imaging data.*

How to Reach the Leonardo Network

Leonardo members, editors, staff and publications are accessible through the Internet in a number of different ways.

Editorial Offices
Leonardo Editorial Office: isast@sfsu.edu
Leonardo Electronic Almanac Editor: lea@mitpress.mit.edu
Leonardo Music Journal Editorial Office: lmj@leonardo.org
Leonardo Reviews: ldr@leonardo.org

Leonardo/ISAST Governing Board of Directors
Roger F. Malina: rmalina@alum.mit.edu
Sonya Rapoport: sonyarap@lmi.net
Stephen Wilson: swilson@sfsu.edu
Martin G. Anderson: martin_g_anderson@ml.com
Mark Resch: resch@onomy.com
Lynn Hershman Leeson: lynn2@well.com
Joel Slayton: joel@well.com
Penelope Finnie: penelopefinnie@mac.com
Piero Scaruffi: editor@scaruffi.com
Beverly Reiser: beverly@idiom.com
Ed Payne: ed@albathion.com
Michael Joaquin Grey: grey147@aol.com
Greg Niemeyer: niemeyer@uclink.berkeley.edu
Anne Brooks Pfister: annepfister@attbi.com
Darlene Tong: dtong@sfsu.edu

Leonard/ISAST Advisory Board
Beverly Reiser: beverly@idiom.com
Nicolas Collins: ncollins@artic.edu
Michael Punt: mpunt@easynet.co.uk
Christine Malina Maxwell: christine@christinesworld.com
Nisar Keshvani: nisar@keshvani.com
Rejane Spitz: rejane@art.puc-rio.br
Michael Naimark: michael@naimark.net
Mark Beam: infinite@beaming.com
Annick Bureaud: annickb@nunc.com
Julio Bermúdez: bermudez@arch.utah.edu
Sundar Sarukkai: sarukkai@nias.iisc.ernet.in

Leonardo Book Series
Joel Slayton, chair: joel@well.com
Douglas Sery: dsery@mit.edu
Roger Malina: rmalina@alum.mit.edu
Annick Bureaud: annickb@nunc.com
Michael Punt: mpunt@easynet.co.uk

Leonardo and LMJ Editorial Board Members
The following is a partial list of *Leonardo* and *Leonardo Music Journal* editorial board members accessible on line:

Roy Ascott: roy.ascott@btinternet.com
Barbara Barthelmes: barthelmes.winkler@snafu.de
Marc Battier: marc.battier@paris4.sorbonne.fr
Jürgen Bräuninger: brauning@nu.ac.za
Paul Brown: paul@paul-brown.com
Annick Bureaud: annick@nunc.com
David Carrier: dxc89@po.cwru.edu
Jürgen Claus: jurclaus@euregio.net
Nicolas Collins: ncollins@artic.edu
Donna Cox: cox@ncsa.uiuc.edu
Ricardo Dal Farra: ricardo@dalfarra.com.ar
Jody Diamond: jody@dartmouth.edu
Michele Emmer: emmer@mat.uniromal.it
Bulat Galeyev: galeyev@prometey.kcn.ru
George Gessert: ggessert@igc.org
István Hargittai: hargittai.istvan@tki.aak.bme.hu
Jonathan Impett: j.impett@uea.ac.uk
Eduardo Kac: ekac@artic.edu
Douglas Kahn: djkahn@ucdavis.edu
Curtis E.A. Karnow: cek@sonnenschein.com
Ray Lauzzana: rlauzzana@yahoo.com
Thomas E. Linehan: Tlinehan@utdallas.edu
Judy Malloy: jmalloy@well.com
Jacques Mandelbrojt: jmandelbrojt@wanadoo.fr
Eduardo Reck Miranda: eduardo.miranda@plymouth.ac.uk
Frieder Nake: nake@infomatik.uni-bremen.de
Jack Ox: jackox@bway.net
Otto Piene: piene@mit.edu
Sheila Pinkel: spinkel@earthlink.net
Larry Polansky: larry.polansky@dartmouth.edu
Frank Popper: fpopper@club-internet.fr
Harry Rand: rand@nmah.si.edu
Robert Root-Bernstein: rootbern@msu.edu
David Rosenboom: david@music.calarts.edu
Itsuo Sakane: sakane@iamas.ac.jp
Sonia Sheridan: Sonia.Sheridan@valley.net
Rejane Spitz: rejane@rdc.puc-rio.br
David Topper: topper@UWinnipeg.ca
Doug Vakoch: vakoch@seti.org
Stephen Wilson: swilson@sfsu.edu
Arthur Woods: awoods@spaceart.net

The Leonardo Electronic Directory
Leonardo maintains an on-line directory called the Leonardo Electronic Directory on the World Wide Web. The directory covers worldwide resources, individuals and organizations in the arts, sciences and technology.
The URL for the Leonardo Electronic Directory is http://mitpress.mit.edu/e-journals/Leonardo/led.dir.html

Free Listing in the Leonardo Electronic Directory for Leonardo Associate Members
Leonardo/ISAST associate members wishing to be included in the directory should send e-mail to isast@sfsu.edu and include their name, addresses and other information that they wish to have posted, including any links to WWW URLs. The submission *must* be submitted in hypertext markup language (HTML) so that we can post the entry immediately in the Leonardo Electronic Directory.