Chemical Mass Balance Application

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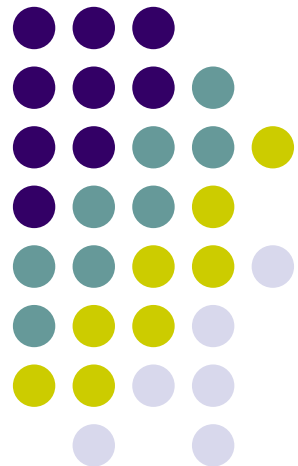
November 2005

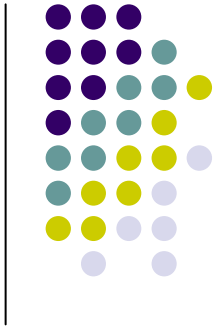
CMB Application



Topics

- CMB Model
- Examples of sources of input data (Note – you will generate your own data for Hyderabad)
- Protocol for applying and validating the model
- Additional resources

Chemical Mass Balance



Equation: $$C_j = \sum_{j=1}^{J} F_{ij} \; S_j \qquad \text{for } i = 1 \text{ to } N$$

Input:

- Ambient concentrations (C_i) and uncertainties (σ_{Cj}), source profiles (F_{ij}), and uncertainties (σ_{Fij}).

Output:

- Source contributions (S_j) and uncertainties (σ_{Sj}).

Measurements:

- Size-classified mass, elements, ions, and carbon concentrations on both ambient and source samples.

CMB Solutions

Minimize differences between calculated and measured values for overdetermined set of equations

$$\chi^2 = \min \Sigma_i \left[(C_i - \mathbf{C_i})^2 / \sigma_{Ci}^2 \right] + \Sigma_i \Sigma_i \left[(F_{ij} - \mathbf{F_{ij}})^2 / \sigma_{Fij}^2 \right]$$

Britt and Luecke, (1973), single sample, bold=true value

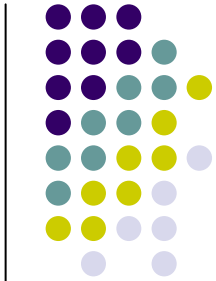
$$\chi^2 = \min \Sigma_i \left[(C_i - \Sigma_j F_{ij} S_j)^2 / (\sigma_{Ci}^2 + \Sigma_j \sigma_{Fij}^2 S_j^2) \right]$$

Effective Variance, Watson et al., (1984), single sample

$$\chi^2 = \min \Sigma_i \left[(C_i - \Sigma_j F_{ij} S_j)^2 / \sigma_{Ci}^2) \right]$$

Ordinary Weighted Least Squares, Friedlander (1973), single sample

Other CMB Solutions



$$S_j = C_i / F_{ij}$$

Tracer solution, Hidy and Friedlander (1971), Winchester and Nifong (1971), single sample

$$\chi^2 = \min \Sigma_k \left[(Mass_k - \Sigma_i C_{ik} / F_{ii})^2 \right]$$

Multiple Linear Regression, Kleinman et al (1980), multiple samples

$$\chi^2 = \min \Sigma_i \, \Sigma_k \left[(C_{ik} - \Sigma_j F_{ij} S_{jk})^2 / \sigma_{Cik}^2 \right]$$

Positive Matrix Factorization, Paatero (1997), multiple samples

Time-Integrated Sampling

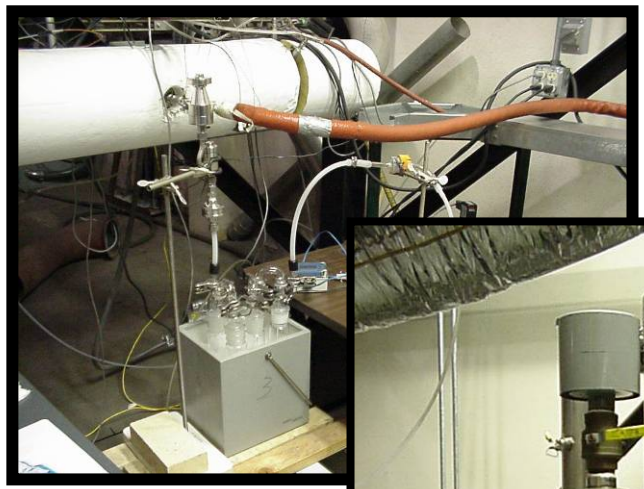
Airmetrics portable MiniVol sampler

$PM_{2.5}$ and PM_{10}

BGI FRM Omni

PM_1, $PM_{2.5}$, and PM_{10}

Dilution Testing of Foundry Emissions



Source-Dominated Sampling (Cooking)

Real-World Cooking

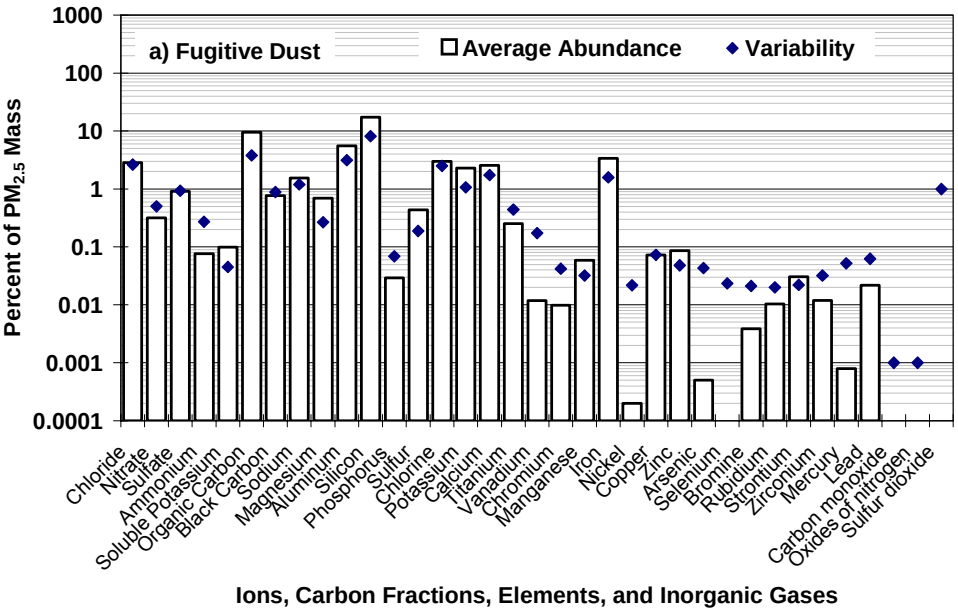
Simulated Cooking

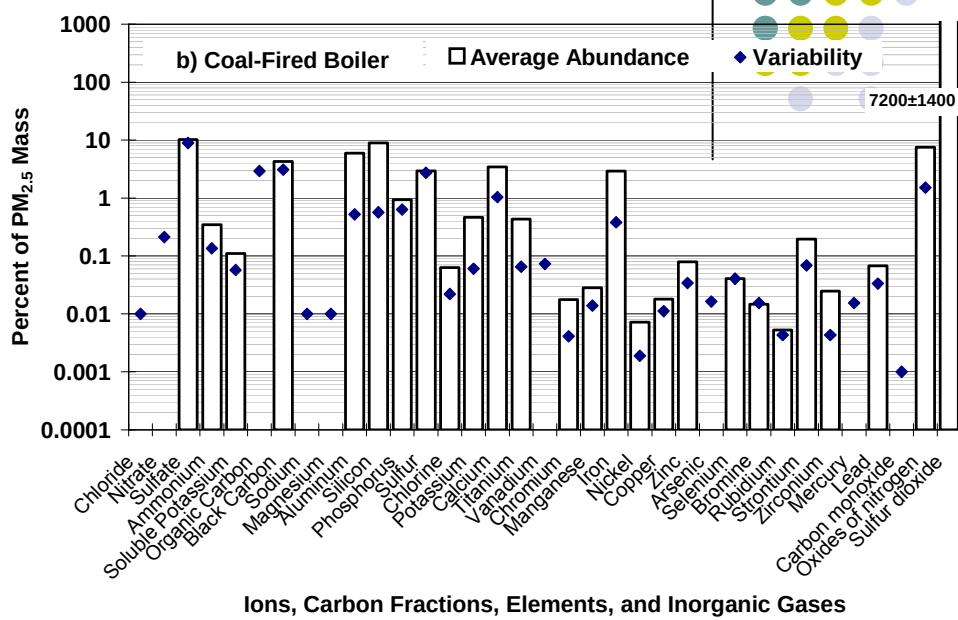
Inspection and Maintenance Compliance Tests

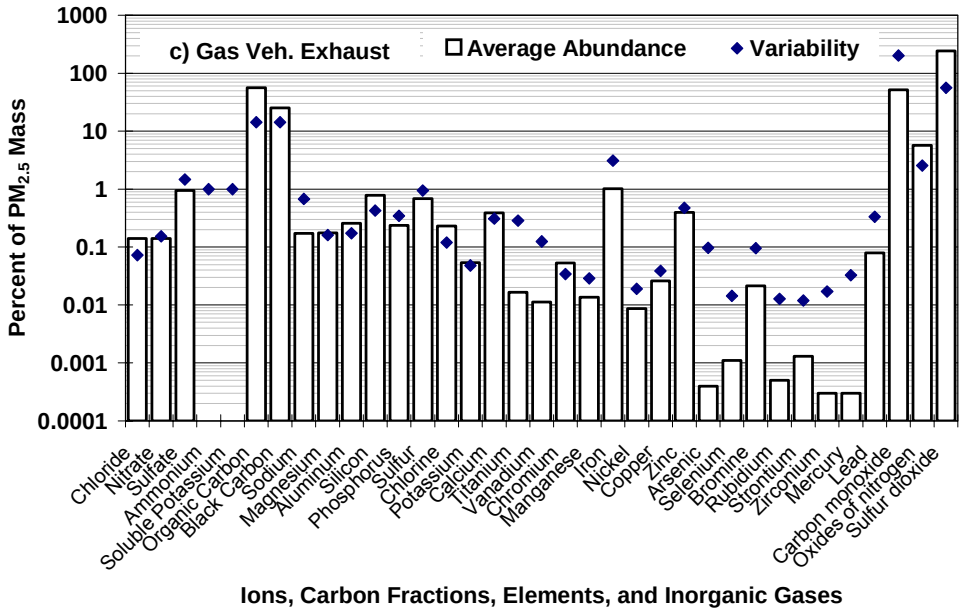
Roadside compliance test in India

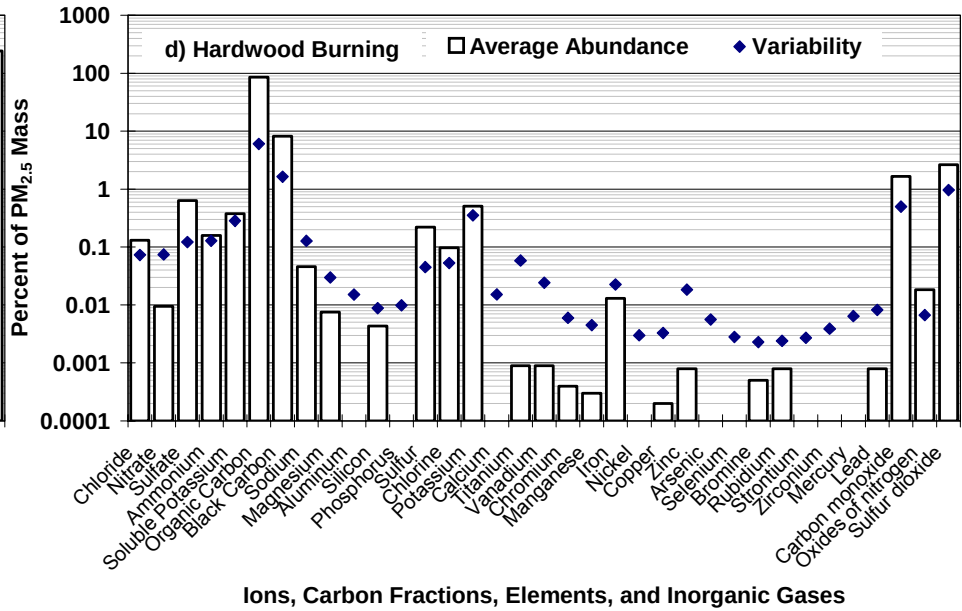
Source Profiles

Commonly measured elements, ions, carbon (Zielinska et al., 1998)





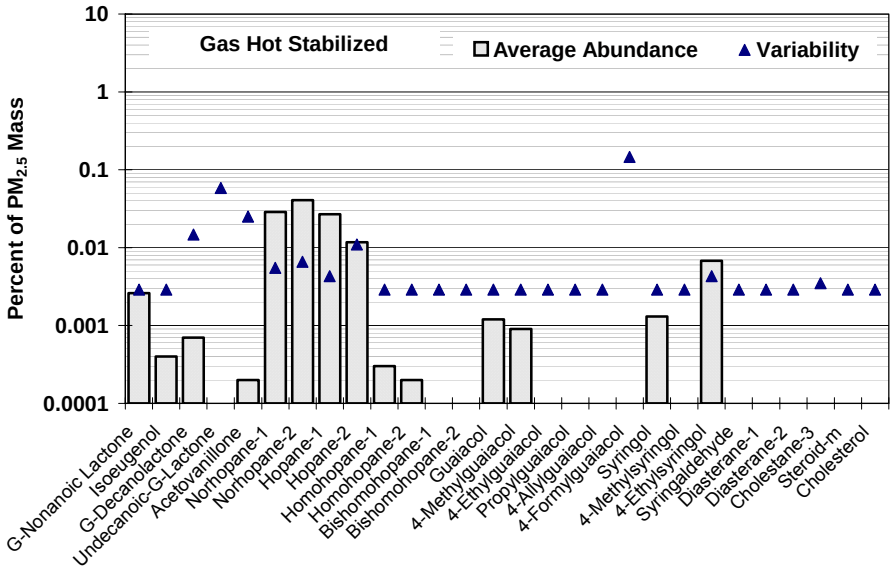


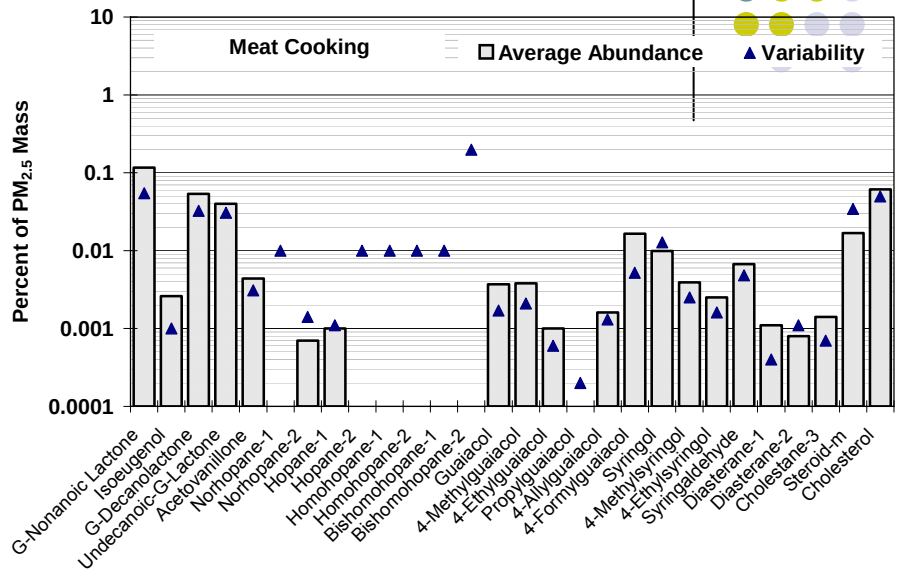


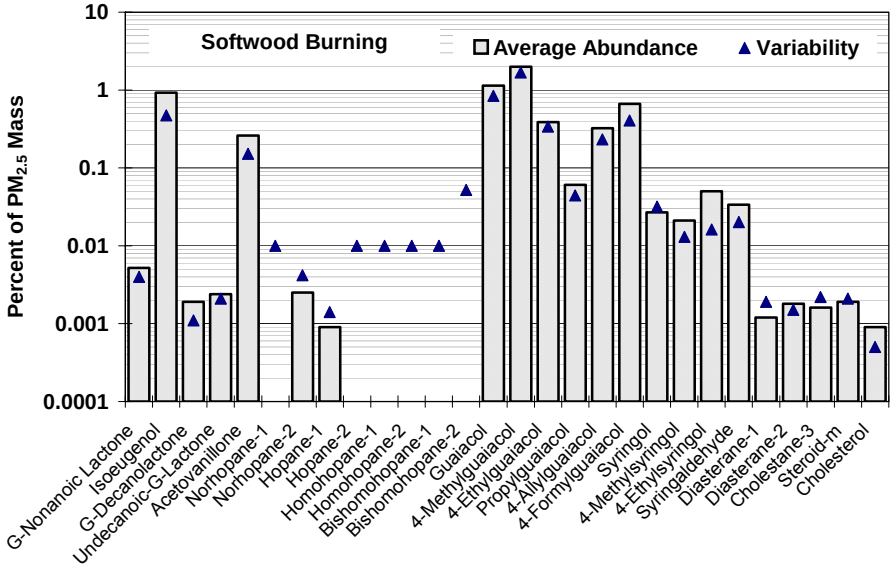
Organic Source Profiles Better Distinguish Among Sources

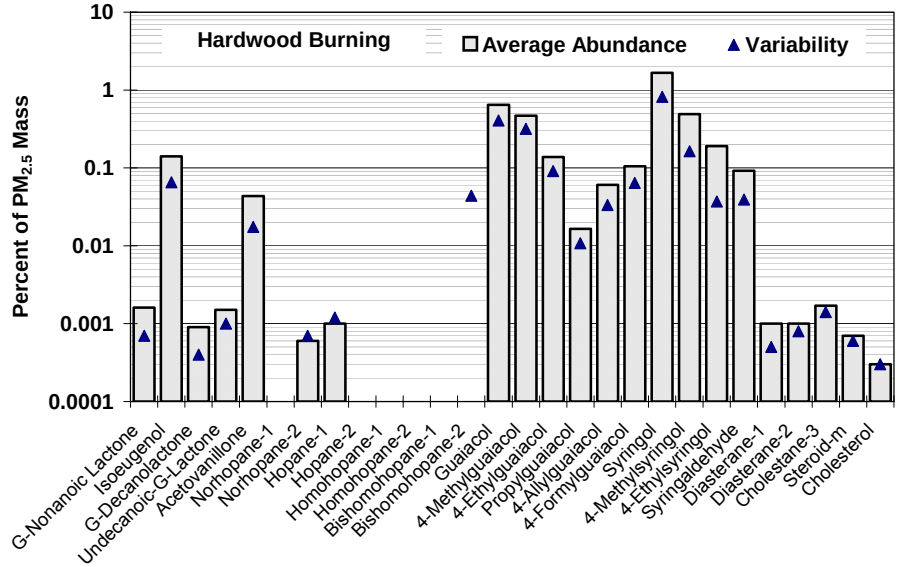
(lactones, hopanes, guaiacols, syringols, steranes, and sterols)

Zielinska et al. (1998)





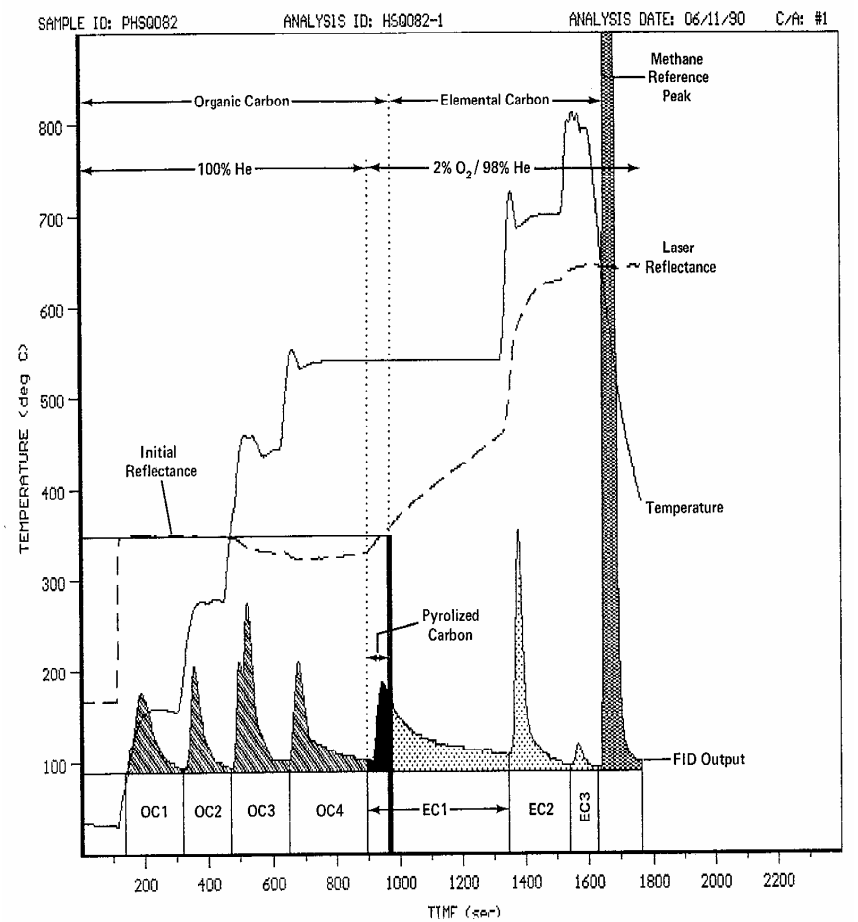




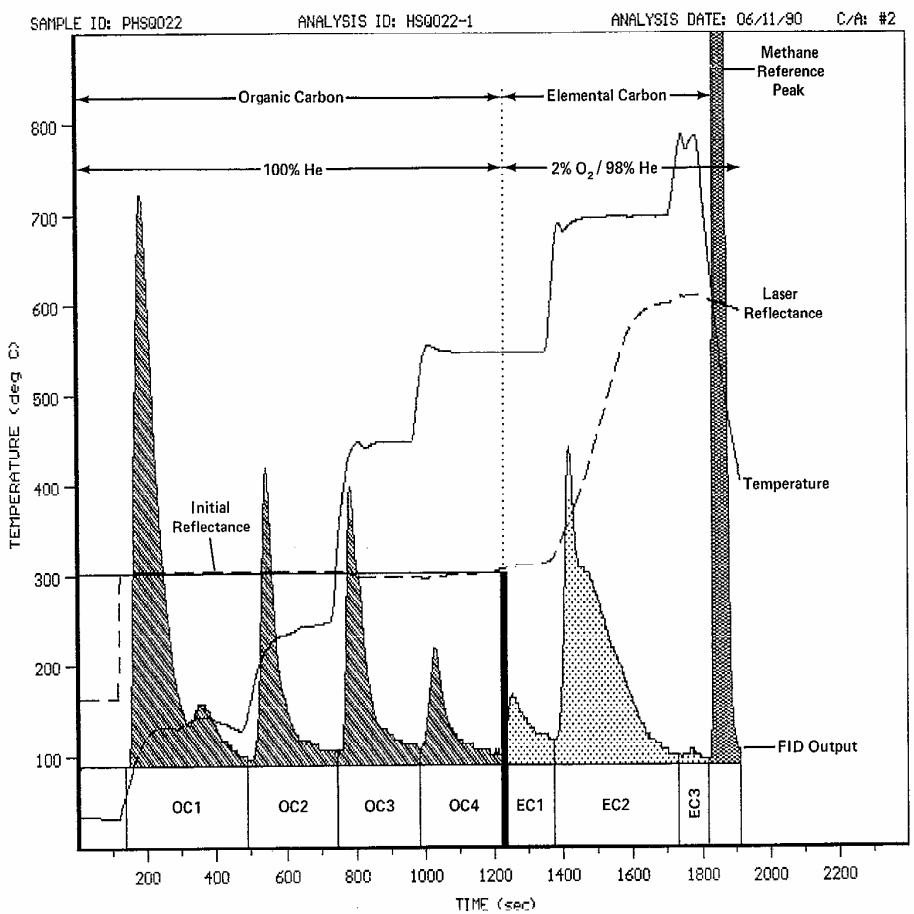
Source Properties can be Operationally Defined

(Thermally evolved carbon fractions, Watson et al., 1994)

Gasoline-fueled vehicles



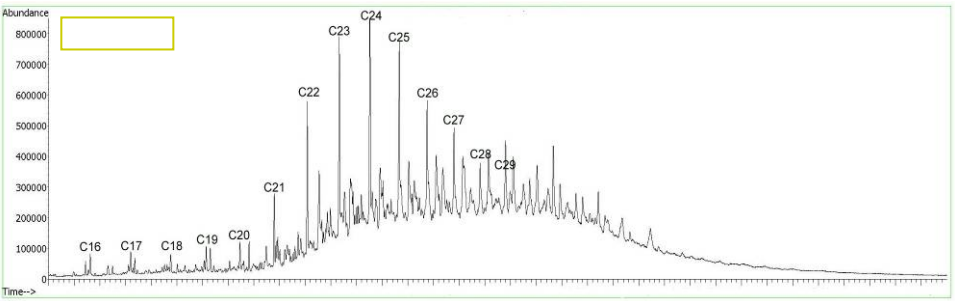
Diesel-fueled vehicles



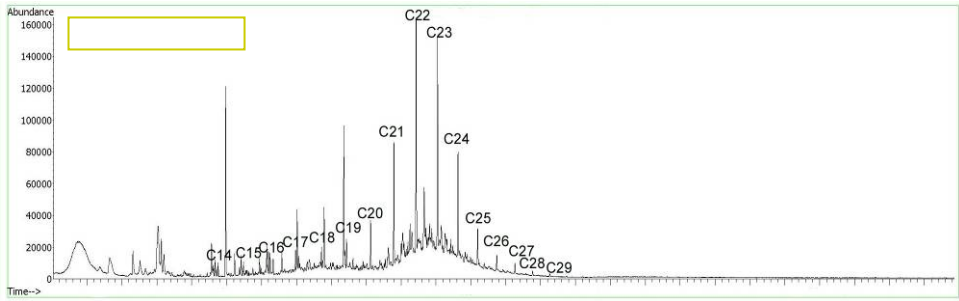
Organic Compounds and Patterns can be Measured on Small Samples

(Example* Chromatograms of Thermal Desorption GC/MS)

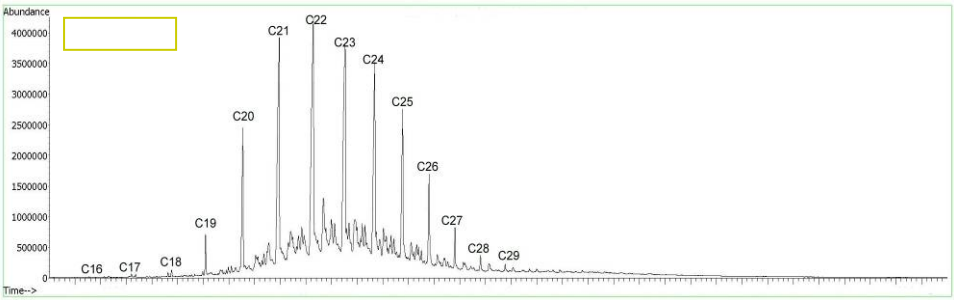
Gasoline



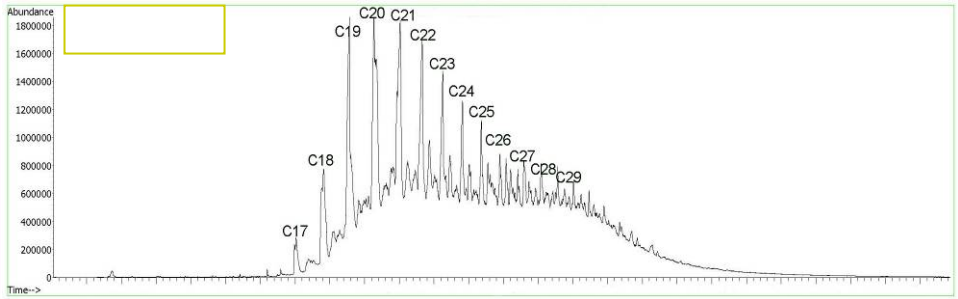
Coal Power Plant



Diesel



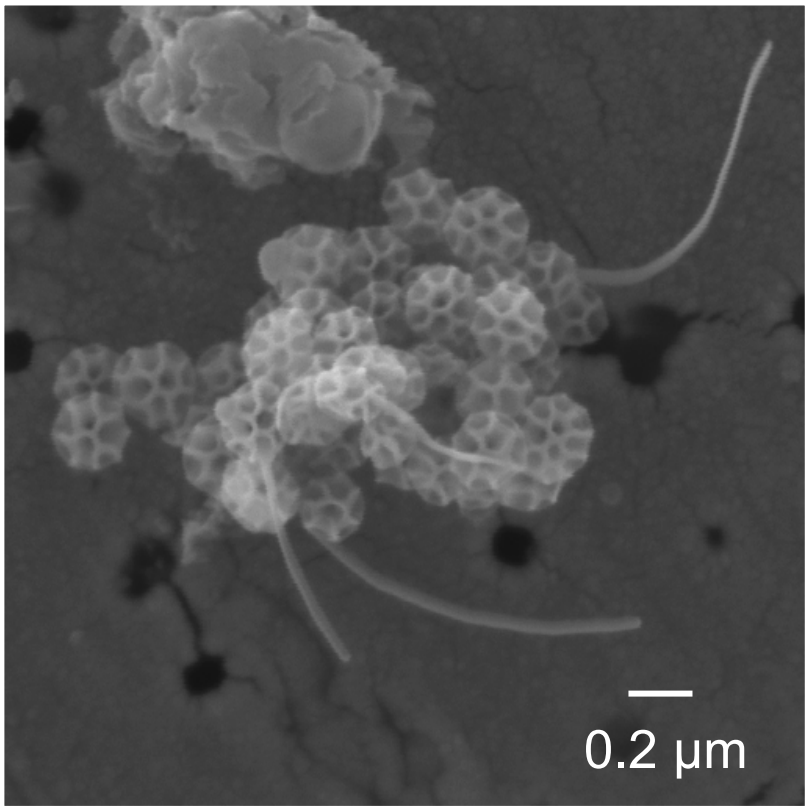
Roadside Dust

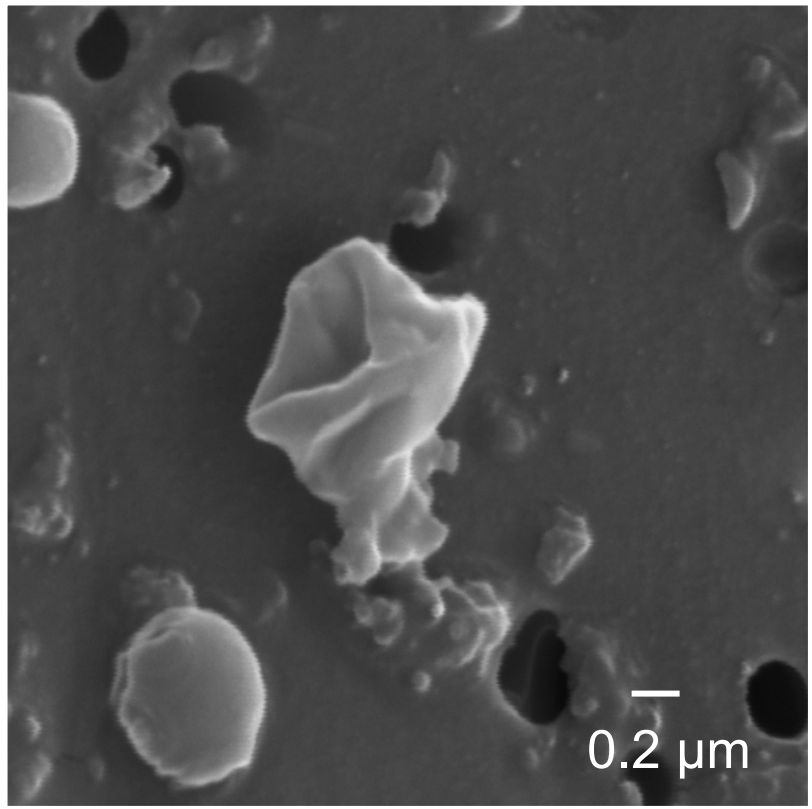


*Ion 57 Chromatogram for alkanes

Ho and Yu, 2004, *J. Chromatogr. A.*, **1059**(1-2)

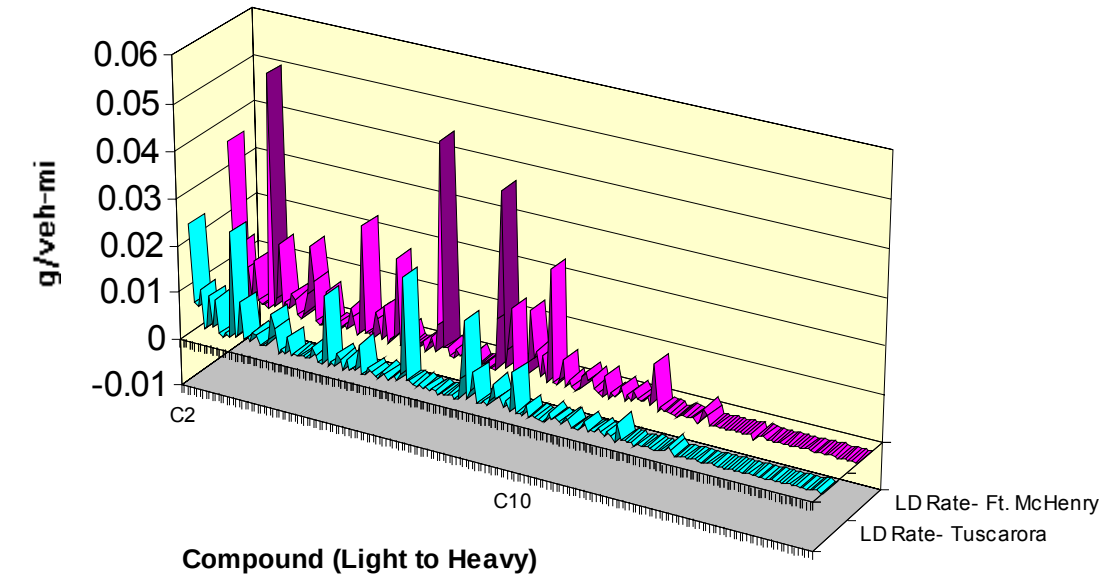
Microscopic Analysis



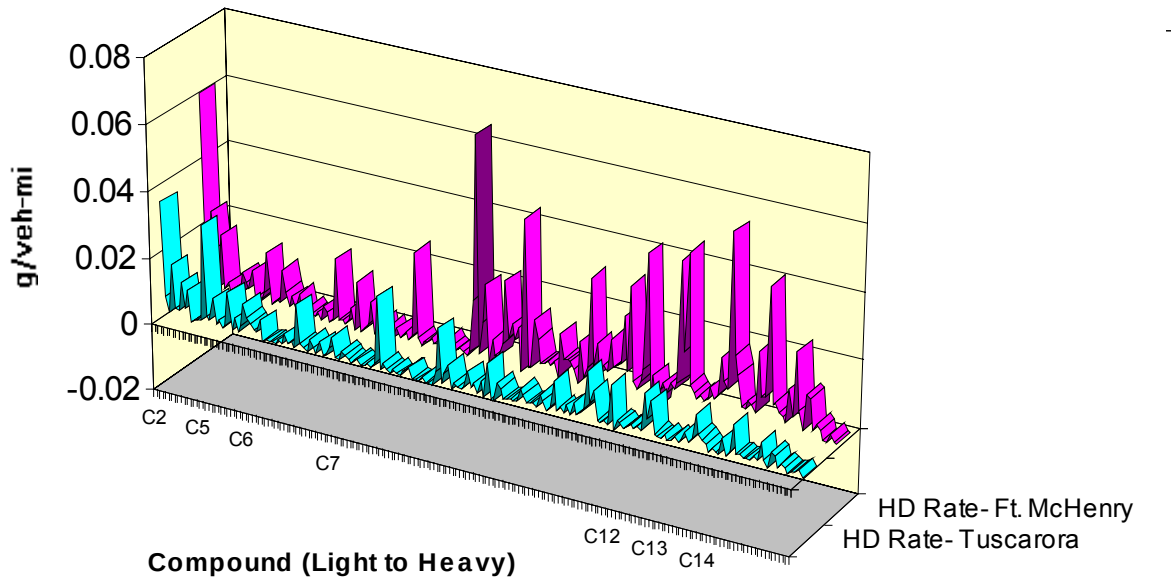


Gases can be Included in Profiles
(Gertler et al., 1996)

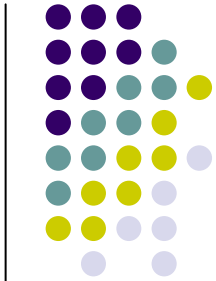
Light Duty Emission Rates



Heavy Duty Emission Rates



Source Composition Data Needs



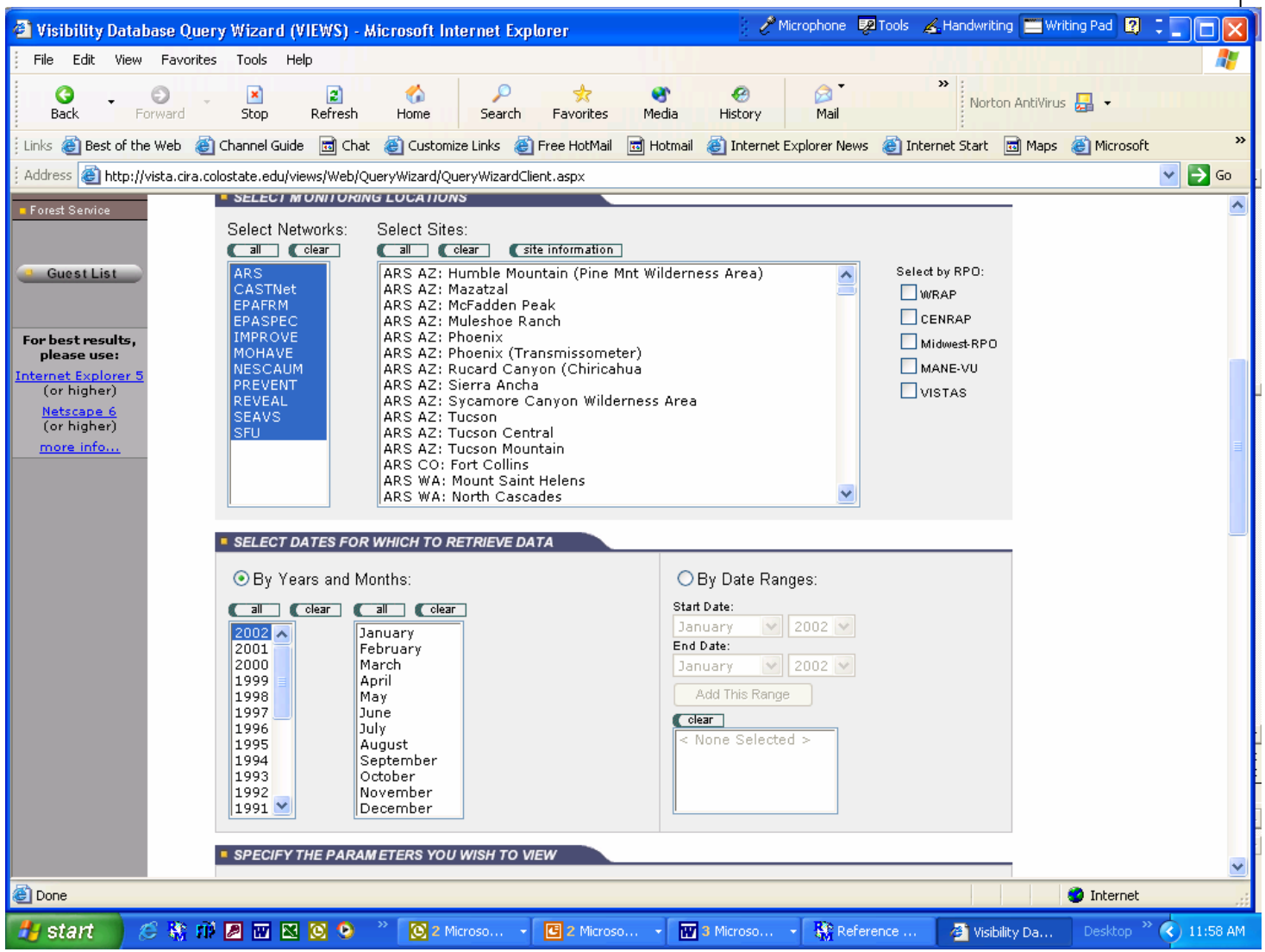
- Profiles for desired source types
- Marker properties (elements, ions, carbon fractions, organic compounds, isotopic abundances, single particle properties)
- Same particle size ranges and species as measured at receptor
- Measurement methods equivalent to those of receptor samples
- Documentation of source characteristics, fuels, and operating parameters
- Source profile uncertainties
- Profiles are as they would appear at the receptor

Source Profile Availability

- Published articles and reports
- U.S. EPA SPECIATE data base
- Researcher data bases
- Original measurements
  - Hot stack compliance sampling (ducted sources, misses condensed species)
  - Dilution stack sampling (ducted sources, more realistic of what is at receptor)
  - Laboratory simulation (dynamometers, test combustors, smog chambers)
  - Source dominated sampling (tunnel, roadside, wildfire plume)
  - Resuspension sampling (fugitive dust, hopper ash, road salt)

Ambient Data Availability

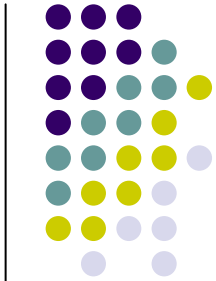
http://vista.cira.colostate.edu/views/Web/QueryWizard/QueryWizardClient.asp
http://www.arb.ca.gov/airways/Datamaintenance/default.asp



Examples of USA Receptor Model Air Quality Findings and Results

- Oregon wood stove emissions standard (Watson, 1979)
- Midwest contributions to east coast sulfate and ozone (Wolff et al., 1977, Lioy et al., 1980, Mueller et al., 1983, Rahn and Lowenthal, 1984)
- Washoe County, Nevada, stove changeout, burning ban, and “squealer” number (Chow et al., 1989)
- California EMFAC emissions model revisions (Fujita et al., 1992, 1994)
- SCAQMD (Los Angeles) grilling emission standard (Rogge, 1993)
- SCAQMD (Los Angeles) street sweeper specification (Chow et al., 1990)
- SCAQMD (Los Angeles) Chino dairy reduction (NH3) regulation (SCAQMD, 1996)
- PM10 SIP implementation of wood burning, road dust, and industrial emission reductions (Davis and Maughan, 1984, Houck et al., 1981, 1982, Cooper et al., 1989)
- Navajo Generating Station SO2 scrubbers (Malm et al., 1989)
- Hayden Generating Station SO2 scrubbers (Watson et al., 1996)
- Mohave Generating Station shutdown (Pitchford et al., 1999)
- Denver Colorado urban visibility standard (Watson et al., 1988)

The CMB Receptor Model and its derivatives are not Statistical



- They don’t test hypotheses or determine statistical significance
- They are physically based with statements of simplifying assumptions and evaluation of deviations from assumptions
- They infer mechanisms and interactions rather than explicitly calculate them
- Receptor models recognize and elucidate patterns in measured components, space and time that bound the types, quantities, and locations of source contributions
- Some of them explicitly use input data uncertainties to weight influence of inputs and estimate uncertainties of outputs

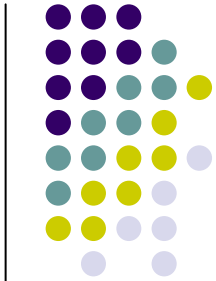
Receptor models can get at secondaries under certain conditions

- OC/EC enrichment factors used to estimate secondary OC contributions (Turpin and Huntzicker, 1991, Gray et al., 1986)
- Secondary organic marker end-products (Pandis, 2001)
- Aerosol evolution to represent changes in profiles (Lewis and Stevens, 1985, Watson et al., 2002)
- 34S or 35S isotopes to follow sulfate changes (Forrest and Newmann, 1973, Hidy, 1987)
- Regional source profiles (Rahn and Lowenthal, 1984, Eatough et al., 1997)
- Eigenvector-derived profiles (Poirot et al., 2001)

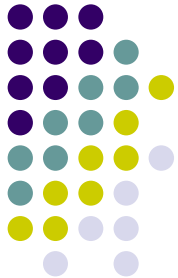
CMB Model Assumptions

- Compositions of source emissions are constant over the period of ambient and source sampling.
- Chemical species do not react with each other (i.e., they add linearly).
- All sources with a potential for significant contribution to the receptor have been identified and have had their emissions characterized.

CMB Model Assumptions (continued)



- The number of sources is less than or equal to the number of chemical species.
- The source compositions are linearly independent of each other.
- Measurement errors are random, uncorrelated, and normally distributed.



CMB8
APPLICATIONS AND VALIDATION PROTOCOL FOR $PM_{2.5}$ AND VOCS

Desert Research Institute Document No. 1808.2F3

June 29, 2001

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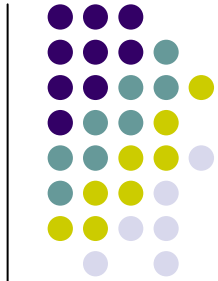
Protocol for Applying and Validating the CMB Model

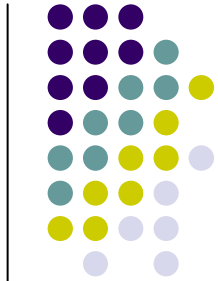


1. Assess general applicability.
2. Configure with source types, source profiles, and chemical species from receptor.
3. Examine model statistics and diagnostics.
4. Determine compliance with model assumptions.

Protocol for Applying and Validating the CMB Model (continued)

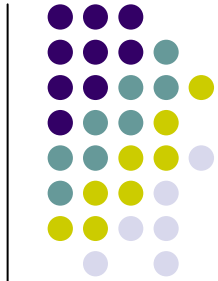
5. Modify model configuration to better comply with assumptions.
6. Test the consistency and stability of CMB results.
7. Evaluate the validity of model results.

1. General Applicability



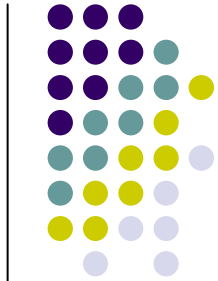
- Samples amenable to or have been chemically speciated
- Potential source contributors identified
- Source profiles measured or approximated
- Marker species in source profiles and receptor measurements
- More receptor species than source types

2. Model Configuration



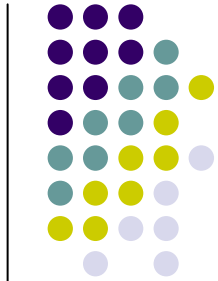
- Receptor species:
  - A value and uncertainty is needed for each species
  - Only one measurement of a given species should be included in the solution (e.g., S and SO4)
  - Values below lower quantifiable limits may be included if uncertainty is set to LQL

2. Model Configuration (continued)



- Source type selection:
  - Common area sources (vehicle exhaust, geological material, secondary sulfate and nitrate)
  - Natural sources (sea salt)
  - Point sources in emissions inventory (coal combustion, residual oil combustion, smelting)
  - Sources identified in PCA or preliminary analysis

2. Model Configuration (continued)



- Source profiles in CMB solution:
  - Upwind point sources
  - Seasonal emitters
  - Non-collinear profiles

3. Model Outputs, Statistics, and Diagnostics

Example of CMB Output

SOURCE CONTRIBUTION ESTIMATES - SITE: PACS1 DATE: 08/13/77 VERSION: 7.0
SAMPLE DURATION 24 START HOUR 0 SIZE: FINE
R SQUARE .98 PERCENT MASS 98.7
CHI SQUARE 1.12 DF 13

SOURCE *	TYPE	SCE(UG/M3)	STD ERR	TSTAT	
1	MARIN	12.3889	2.2457	5.5167	Marine Aerosol
3	UDUST	9.5917	1.3876	6.9127	Urban Dust
4	AUTPB	10.0835	1.4942	6.7486	Leaded Motor Vehicle Exhaust
5	RDOIL	11.0603	1.9239	5.7490	Residual Oil Combustion
8	KRAFT	4.6896	5.0467	.9292	Kraft Recovery Boiler
11	ALPRO	10.6023	3.5896	2.9536	Aluminum Pot Line
12	STEEL	8.6729	1.3771	6.2979	Steel Blast Furnace
13	FERMN	11.8754	1.8321	6.4820	Ferromanganese Furnace

MEASURED CONCENTRATION FINE/COARSE/TOTAL:
80.0+- 8.0/ 80.0+- 8.0/ 160.0+- 11.3

UNCERTAINTY/SIMILARITY CLUSTERS VERSION: 7.0			SUM OF CLUSTER SOURCES	
1	8		17.078+-	4.241
1	5	8	28.139+-	3.833

SPECIES CONCENTRATIONS - SITE: PACS1 DATE: 08/13/77 VERSION: 7.0
SAMPLE DURATION 24 START HOUR 0 SIZE: FINE
R SQUARE .98 PERCENT MASS 98.7
CHI SQUARE 1.12 DF 13

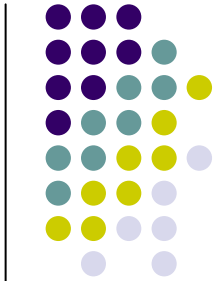
SPECIES		I[a]	MEAS[b]		CALC[b]		RATIO C/M		RATIO R/U
C1	TOT	T	80.00000+-	8.00000	78.96461+-	4.82449	.99+-	.12	-.1
C9	F		.88300+-	.08800	.67644+-	.24792	.77+-	.29	-.8
C11	NA	*	6.93000+-	.69300	6.97025+-	.56446	1.01+-	.13	.0
C12	MG	*	.43000+-	.04300	1.60951+-	.62627	3.74+-	1.50	1.9
C13	AL	*	4.66000+-	.46600	4.02418+-	.88919	.86+-	.21	-.6
C14	SI	*	3.02000+-	.30200	2.92212+-	.13329	.97+-	.11	-.3
C16	S		2.95000+-	.29500	3.02466+-	.31807	1.03+-	.15	.2
C17	CL	*	5.95000+-	.59500	5.69381+-	1.24836	.96+-	.23	-.2
C19	K	*	1.64000+-	.16400	1.73084+-	.46411	1.06+-	.30	.2
C20	CA	*	1.78000+-	.17800	1.43537+-	.11366	.81+-	.10	-1.6
C22	TI	*	.08300+-	.00800	.10088+-	.01630	1.22+-	.23	1.0
C23	V	*	.37200+-	.03700	.39757+-	.08308	1.07+-	.25	.3
C24	CR	*	.31500+-	.03200	.20976+-	.12151	.67+-	.39	-.8
C25	MN	*	2.99000+-	.29900	2.82844+-	.14115	.95+-	.11	-.5
C26	FE	*	4.53000+-	.45300	4.24446+-	.33269	.94+-	.12	-.5
C28	NI	*	.76500+-	.07700	.68246+-	.13428	.89+-	.20	-.5
C29	CU	*	.04400+-	.00400	.05274+-	.00510	1.20+-	.16	1.3
C30	ZN	*	.22500+-	.02300	.26786+-	.03966	1.19+-	.21	.9
C35	BR	*	.41900+-	.04200	.56133+-	.17386	1.34+-	.44	.8
C82	PB	*	2.53000+-	.25300	2.13749+-	.30300	.84+-	.15	-1.0
C201	OC	*	7.54000+-	.75400	8.50978+-	1.35632	1.13+-	.21	.6
C202	EC	*	1.42000+-	.14200	1.33579+-	.34012	.94+-	.26	-.2
C203	SO4	*	10.30000+-	1.03400	9.78819+-	1.47514	.95+-	.17	-.3
C204	NO3	*	.63800+-	.06400	.88402+-	.35938	1.39+-	.58	.7

3. Model Outputs, Statistics, and Diagnostics (cont.)

Source Contribution Display

Output/Statistic/Code	Abbreviation	Description
Source Contribution Estimate	SCE	Primary output: Source contribution ($\mu g/m^3$).
Standard Error	STDERR	Primary output: The variance of the SCE. [Target: << SCE]
t-statistic	T-STAT	Statistic: The ratio of the SCE to its STDERR. A high T-STAT suggests a non-zero SCE. [Target: > 2.0]
R-square	R-SQUARE	Statistic: Used to measure the variance in theambient species concentrations which is explained by the calculated species concentrations. Ranges from 0 to 1.0. [Target: 0.8 to 1.0]

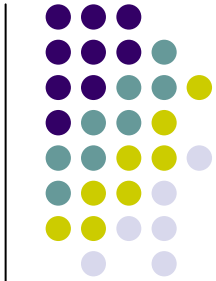
3. Model Outputs, Statistics, and Diagnostics (cont.)



Source Contribution Display (continued)

Output/Statistic/Code	Abbreviation	Description
Chi-square	CHI-SQUARE	Statistic: Used to consider the uncertainties of the calculated species concentrations. A high CHI-SQUARE suggests that the model has not explained the species data very well. [Target: 1.0 to 4.0]
Percent Mass Accounted For	PERCENT MASS or % MASS	Statistic: Used to track the % of ambient mass explained by the sum of the SCEs. A % MASS near 100% can be misleading because a poor fit can force a high % MASS. [Target: 100% ± 20%]

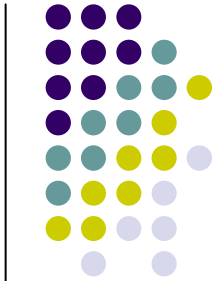
3. Model Outputs, Statistics, and Diagnostics (continued)



Source Contribution Display (continued)

Output/Statistic/Code	Abbreviation	Description
Degrees of Freedom	DF	Statistic: Number of species in fit minus number of sources in fit.
Site/Sample	SITE, etc.	Status: Data being used in the fit.
Uncertainty/Similarity Clusters	U/S Clusters	Diagnostic: Summary of singular value decomposition analysis. It shows clusters of sources which the model cannot easily distinguish between and that are likely to be interfering with the model's ability to provide a good set of SCEs. [Target: No Clusters]

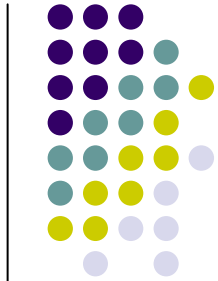
3. Model Outputs, Statistics, and Diagnostics (continued)



Source Contribution Display (continued)

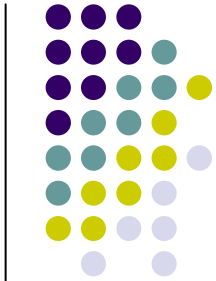
Output/Statistic/Code	Abbreviation	Description
Sum of Combined Sources	SUM ±	Supplemental output: Supplement to U/S Clusters. It estimates the sum of SCEs of the sources in a cluster and the standard error of the sum. The standard error of the sum follows the ±.

4. Evaluate Model Assumptions



- Source compositions constant
- Chemical species add linearly
- All contributing sources included
- Source profiles linearly independent
- Number of sources less than number of species
- Measurement uncertainties random, uncorrelated, and normally distributed

CMB Model Test Methods and Results

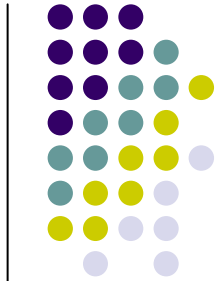


- Constant compositions (substitute different profiles, randomly perturb profiles)– can tolerate substantial variability
- Non-reactive species (estimate profile fractionation, use)– little known
- All source types identified (look for deficits in marker species, unusual values>LQL)– minor contributors can be left out
- Number of sources less than number of species (always the case)– the larger the difference the better

CMB Model Test Methods and Results

- Source contributions linearly independent (MPIN, collinearity clusters)– degree depends on variability of source profile
- Measurement error distribution (randomized tests with non-normal distributions)– non much difference

5. Adjust Model Inputs

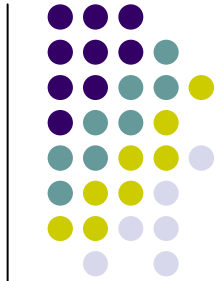


- Increase uncertainties of profile abundances or provide different profile composites
- Create “aged” source profiles with aerosol evolution model
- Identify and characterize missing sources.
- Measure additional species at source and receptor. Stratify samples by meteorological regime

6. Verify Consistency and Stability

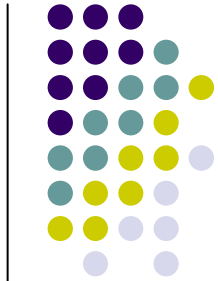
- Substitute different profiles for the same source type
- Add or drop species from the fit
- Examine source contributions to species.
- Examine modified psuedo inverse matrix

7. Evaluate and Reconcile Source Apportionments



- Compare source contributions among nearby sites
- Compare source contribution variations over time with expected emissions and meteorological variations.
- Apply other receptor methods and compare results
- Apply dispersion models and compare results

Protocol for Reconciling Differences Among Receptor and Dispersion Models



1. Compare CMB and DM results.
2. Verify input data in both models.
3. Recompare results.
4. Refine CMB model inputs.
5. Recompare results.
6. Refine dispersion model inputs.
7. Recompare.
8. "… if it is clearly evident that the dispersion model is not valid, the CMB estimates should be used as the basis for control strategy development. However, if the disparity is not clearly attributable to either model alone, the dispersion model should be used for control strategy development."

Conclusions

- The applications and validation protocol results in more accurate source apportionments.
- Though the protocol does not solve every problem encountered in the CMB, it does identify that a problem exists and suggests some alternatives for solving it.
- Reconciliation of CMB source apportionments with other source apportionment methods yields more accurate results.

References

- Britt, H.I., and R.H. Luecke (1973). The estimation of parameters in nonlinear, implicit models. Technometrics, 15:233-247.
- Brook, J.R.; Vega, E.; Watson, J.G. Chapter 7: Receptor Methods, in Particulate Matter Science for Policy Makers - A NARSTO Assessment, Part 1. Hales, J.M., Hidy, G.M., Eds.; Cambridge University Press: London, UK, 2004, pp. 235-281.
- Chow, J.C.; Watson, J.G.; Egami, R.T.; Frazier, C.A.; and Lu, Z. (1989). The State of Nevada Air Pollution Study (SNAPS): Executive summary. Report No. DRI 8086.5E. Prepared for State of Nevada, Carson city, NV, by Desert Research Institute, Reno, NV.
- Chow, J.C.; Watson, J.G.; Egami, R.T.; Frazier, C.A.; Lu, Z.; Goodrich, A.; and Bird, A. (1990). Evaluation of regenerative-air vacuum street sweeping on geological contributions to PM10. J. Air & Waste Manage. Assoc., 40(8):1134-1142.
- Chow, J.C.; and Watson, J.G. (2002). Review of PM2.5 and PM10 apportionment for fossil fuel combustion and other sources by the chemical mass balance receptor model. Energy & Fuels, 16(2):222-260. doi: 10.1021/ef0101715.
- Chow, J.C.; Engelbrecht, J.P.; Watson, J.G.; Wilson, W.E.; Frank, N.H.; and Zhu, T. (2002). Designing monitoring networks to represent outdoor human exposure. Chemosphere, 49(9):961-978.
- Cooper, J.A.; Miller, E.A.; Redline, D.C.; Spidell, R.L.; Caldwell, L.M.; Sarver, R.H.; and Tansyy, B.L. (1989). PM10 source apportionment of Utah Valley winter episodes before, during, and after closure of the West Orem steel plant. Prepared for Kimball, Parr, Crockett and Waddops, Salt Lake City, UT, by NEA, Inc., Beaverton, OR.
- Daisey, J.M.; Cheney, J.L.; and Lioy, P.J. (1986). Profiles of organic particulate emissions from air pollution sources: status and needs for receptor source apportionment modeling. J. Air Pollution Control Assoc., 36(1):17-33.
- Davis, B.L.; and Maughan, A.D. (1984). Observation of heavy metal compounds in suspended particulate matter at East Helena, Montana. J. Air Pollution Control Assoc., 34(12):1198-1202.
- Demerjian, K.L. (2000). A review of national monitoring networks in North America. Atmos. Environ., 34(12-14):1861-1884.

References (continued)

- Eatough, D.J.; Du, A.; Joseph, J.M.; Caka, F.M.; Sun, B.; Lewis, L.; Mangelson, N.F.; Eatough, M.; Rees, L.B.; Eatough, N.L.; Farber, R.J.; and Watson, J.G. (1997). Regional source profiles of sources of SOX at the Grand Canyon during Project MOHAVE. J. Air & Waste Manage. Assoc., 47(2):101-118.
- England, G.C.; Zielinska, B.; Loos, K.; Crane, I.; and Ritter, K. (2000). Characterizing PM2.5 emission profiles for stationary sources: Comparison of traditional and dilution sampling techniques. Fuel Processing Technology, 65:177-188.
- Forrest, J.; and Newmann, L. (1973). Sampling and analysis of atmospheric sulfur compounds for isotope ratio studies. Atmos. Environ., 7(5):561-573.
- Friedlander, S.K. (1973). Chemical element balances and identification of air pollution sources. Environ. Sci. Technol., 7:235-240.
- Fujita, E.M.; Croes, B.E.; Bennett, C.L.; Lawson, D.R.; Lurmann, F.W.; and Main, H.H. (1992). Comparison of emission inventory and ambient concentration ratios of CO, NMOG, and NOx in California's South Coast Air Basin. J. Air & Waste Manage. Assoc., 42(3):264-276.
- Fujita, E.M.; Watson, J.G.; Chow, J.C.; and Lu, Z. (1994). Validation of the chemical mass balance receptor model applied to hydrocarbon source apportionment in the Southern California Air Quality Study. Environ. Sci. Technol., 28(9):1633-1649.
- Gertler, A.W.; Fujita, E.M.; Pierson, W.R.; and Wittorff, D.N. (1996). Apportionment of NMHC tailpipe vs non-tailpipe emissions in the Fort McHenry and Tuscarora mountain tunnels. Atmos. Environ., 30(12):2297-2305.
- Gordon, G.E.; Pierson, W.R.; Daisey, J.M.; Lioy, P.J.; Cooper, J.A.; Watson, J.G.; and Cass, G.R. (1984). Considerations for design of source apportionment studies. Atmos. Environ., 18(8):1567-1582.
- Gray, H.A.; Cass, G.R.; Huntzicker, J.J.; Heyerdahl, E.K.; and Rau, J.A. (1986). Characteristics of atmospheric organic and elemental carbon particle concentrations in Los Angeles. Environ. Sci. Technol., 20(6):580-589.
- Hidy, G.M. (1987). Conceptual design of a massive aerometric tracer experiment (MATEX). J. Air Pollution Control Assoc., 37(10):1137-1157.
- Hidy, G.M., and S.K. Friedlander (1971). The nature of the Los Angeles aerosol. In Proceedings of the Second International Clean Air Congress, Academic Press, New York, pp. 391-404
- Ho, S.S.H.; Yu, J.Z. In-injection port thermal desorption and subsequent gas chromatography-mass spectrometric analysis of polycyclic aromatic hydrocarbons and n-alkanes in atmospheric aerosol samples; J. Chromatogr. A 2004, 1059(1-2), 121-129.

References (continued)

- Houck, J.E.; Cooper, J.A.; Core, J.E.; Frazier, C.A.; and deCesar, R.T. (1981). Hamilton Road Dust Study: Particulate source apportionment analysis using the chemical mass balance receptor model. Prepared for Concord Scientific Corporation, by NEA Laboratories, Inc., Beaverton, OR.
- Houck, J.E.; Cooper, J.A.; Frazier, C.A.; and deCesar, R.T. (1982). East Helena Source Apportionment Study: Particulate source apportionment analysis using the chemical mass balance receptor model. Prepared for State of Montana, Dept. of Health & Environmental Sciences, Helena, MT, by NEA Laboratories, Inc., Beaverton, OR.
- Javitz, H.S., J.G. Watson, J.P. Guertin, and P.K. Mueller (1988). Results of a receptor modeling feasibility study. JAPCA, 38:661-667.
- Kleinman, M.T., B.S. Pasternack, M. Eisenbud, and T.J. Kneip (1980). Identifying and estimating the relative importance of sources of airborne particulates. Environ. Sci. Technol., 14:62-65.
- Lewis, C.W.; and Stevens, R.K. (1985). Hybrid receptor model for secondary sulfate from an SO2 point source. Atmos. Environ., 19(6):917-924.
- Lioy, P.J.; Samson, P.J.; Tanner, R.L.; Leaderer, B.P.; Minnich, T.; and Lyons, W.A. (1980). The distribution and transport of sulfate "species" in the New York area during the 1977 Summer Aerosol Study. Atmos. Environ., 14:1391-1407.
- Lu, Z.(1996). Temporal and spatial analysis of VOC source contributions for Southeast Texas. Ph.D.Dissertation, University of Nevada, Reno.
- Malm, W.C.; Pitchford, M.L.; and Iyer, H.K. (1989). Design and implementation of the Winter Haze Intensive Tracer Experiment - WHITEX. In Transactions, Receptor Models in Air Resources Management, J.G. Watson, Ed. Air & Waste Management Association, Pittsburgh, PA, pp. 432-458.
- Mueller, P.K.; Hidy, G.M.; Baskett, R.L.; Fung, K.K.; Henry, R.C.; Lavery, T.F.; Nordi, N.J.; Lloyd, A.C.; Thrasher, J.W.; Warren, K.K.; and Watson, J.G. (1983). Sulfate Regional Experiment (SURE): Report of findings. Report No. EA-1901. Prepared by Electric Power Research Institute, Palo Alto, CA.
- Paatero, P. (1997). Least squares formulation of robust non-negative factor analysis. Chemom. Intell. Lab. Sys., 37:23-35.
- Pandis, S. (2001). Secondary organic aerosol: Precursors, composition, chemical mechanisms, and environmental conditions. Presentation at the Secondary Organic Aerosols Workshop in Durango, CO. Fort Lewis College, Durango, CO.
- Pitchford, M.L.; Green, M.C.; Kuhns, H.D.; Tombach, I.H.; Malm, W.C.; Scruggs, M.; Farber, R.J.; Mirabella, V.A.; White, W.H.; McDade, C.; Watson, J.G.; Koracin, D.; Hoffer, T.E.; Lowenthal, D.H.; Vimont, J.C., et al. (1999). Project MOHAVE, Final Report. Prepared by U.S. Environmental Protection Agency, Region IX, San Francisco, CA. http://www.epa.gov/region09/air/mohave/report.html.

References (continued)

- Poirot, R.L.; Wishinski, P.R.; Hopke, P.K.; and Polissar, A.V. (2001). Comparitive application of multiple receptor methods to identify aerosol sources in northern Vermont. Environ. Sci. Technol., 35(23):4622-4636.
- Rahn, K.A.; and Lowenthal, D.H. (1984). Northeastern and midwestern contributions to pollution aerosol in the northwestern United States. Science, 223:132.
- Rahn, K.A.; and Lowenthal, D.H. (1984). Elemental tracers of distant regional pollution aerosols. Science, 223:132-139.
- Rogge, W.F. (1993). Molecular tracers for sources of atmospheric carbon particles: Measurements and model predictions. Ph.D. Dissertation, California Institute of Technology, Pasadena, CA.
- South Coast Air Quality Management District (1996). 1997 air quality maintenance plan: Appendix V, Modeling and attainment demonstrations. Prepared by South Coast Air Quality Management District, Diamond Bar, CA. http://www.aqmd.gov/aqmp/97aqmp/.
- Turpin, B.J.; and Huntzicker, J.J. (1991). Secondary formation of organic aerosol in the Los Angeles Basin: A descriptive analysis of organic and elemental carbon concentrations. Atmos. Environ., 25A(2):207-215.
- U.S.EPA (1999). SPECIATE: EPA's repository of total organic compound and particulate matter speciated profiles for a variety of sources for use in source apportionment studies. Prepared by U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC. http://www.epa.gov/ttn/chief/software/speciate/.
- Watson, J.G.(1979). Chemical element balance receptor model methodology for assessing the sources of fine and total suspended particulate matter in Portland, Oregon. Ph.D.Dissertation, Oregon Graduate Center, Beaverton, OR.
- Watson, J.G. (1984). Overview of receptor model principles. J. Air Pollution Control Assoc., 34(6):619-623.
- Watson, J.G., J.A. Cooper, and J.J. Huntzicker (1984). The effective variance weighting for least squares calculations applied to the mass balance receptor model. Atmos. Environ., 18:1347-1355.

References (continued)

- Watson, J.G.; Chow, J.C.; Richards, L.W.; Andersen, S.R.; Houck, J.E.; and Dietrich, D.L. (1988). The 1987-88 Metro Denver Brown Cloud Air Pollution Study, Volume III: Data interpretation. Report No. DRI 8810.1. Prepared for 1987-88 Metro Denver Brown Cloud Study, Inc., Greater Denver Chamber of Commerce, Denver, CO, by Desert Research Institute, Reno, NV.
- Watson, J.G.; Chow, J.C.; Lowenthal, D.H.; Pritchett, L.C.; Frazier, C.A.; Neuroth, G.R.; and Robbins, R. (1994). Differences in the carbon composition of source profiles for diesel- and gasoline-powered vehicles. Atmos. Environ., 28(15):2493-2505.
- Watson, J.G.; Blumenthal, D.L.; Chow, J.C.; Cahill, C.F.; Richards, L.W.; Dietrich, D.; Morris, R.; Houck, J.E.; Dickson, R.J.; and Andersen, S.R. (1996). Mt. Zirkel Wilderness Area reasonable attribution study of visibility impairment, Vol. II: Results of data analysis and modeling. Prepared for Colorado Department of Public Health and Environment, Denver, CO, by Desert Research Institute, Reno, NV.
- Watson, J.G.; Fujita, E.M.; Chow, J.C.; Zielinska, B.; Richards, L.W.; Neff, W.D.; and Dietrich, D. (1998). Northern Front Range Air Quality Study. Final report. Prepared for Colorado State University, Fort Collins, CO, by Desert Research Institute, Reno, NV. http://charon.cira.colostate.edu/DRIFinal/ZipFiles/.
- Watson, J.G. (2002). Visibility: Science and regulation. JAWMA, 52:628-713.
- Watson, J.G.; Zhu, T.; Chow, J.C.; Engelbrecht, J.P.; Fujita, E.M.; and Wilson, W.E. (2002). Receptor modeling application framework for particle source apportionment. Chemosphere, 49(9):1093-1136.
- Watson, J.G.; Chow, J.C.; Lowenthal, D.H.; Robinson, N.F.; Cahill, C.F.; and Blumenthal, D.L. (2002). Simulating changes in source profiles from coal-fired power stations: Use in chemical mass balance of PM2.5 in the Mt. Zirkel Wilderness. Energy & Fuels, 16(2):311-324.
- Watson, J.G.; Chow, J.C. Receptor models, in Air Quality Modeling -Theories, Methodologies, Computational Techniques, and Available Databases and Software. Vol. II - Advanced Topics, Zannetti, P., Ed.; Air and Waste Management Association and the EnviroComp Institute: Pittsburgh, PA, 2005, pp. 455-501.
- Watson, J.G.; Chow, J.C. Receptor models for air quality management; EM 2004, 9(Oct.), 27-36.
- Winchester, J.W., and G.D. Nifong (1971). Water pollution in Lake Michigan by trace elements from aerosol fallout. Water Air and Soil Pollution, 1:50-64.
- Wolff, G.T.; Lioy, P.J.; Wight, G.D.; Meyers, R.E.; and Cederwall, R.T. (1977). An investigation of long-range transport of ozone across the midwestern and eastern United States. Atmos. Environ., 11:797-802.
- Zielinska, B.; McDonald, J.D.; Hayes, T.; Chow, J.C.; Fujita, E.M.; and Watson, J.G. (1998). Northern Front Range Air Quality Study, Volume B: Source measurements. Prepared for Colorado State University, Fort Collins, CO, by Desert Research Institute, Reno, NV. http://charon.cira.colostate.edu/DRIFinal/ZipFiles/.