APPENDIX TO DESCRIPTION OF IMS

VPP and LPP ALGORITHMS

C. L. Poor
Washington D. C.

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VPP ALGORITHM DESCRIPTION

The VPP accepts inputs from the LPP, and computes boat speed for a variety of conditions. It also tabulates certificates. The VPP consists of a number of subprograms, each performing part of the computation.

In this brief description, some liberties have been taken with the names of subprograms and some parts of the programs have been omitted, in the interest of simplicity.

The VPP consists of an aerodynamic model, a hydrodynamic model, an equilibrium routine, an optimizing routine, and a driver program for selecting the cases to be computed.

The hydrodynamic model was described in part in the main text. However, for completeness it will be described here in more detail.

VPP STRUCTURE:

The VPP driver program selects a set of wind speeds and courses for which performance estimates are desired, and provides initial guesses as to the boat speed and heel angle.

The hydrodynamic model computes the hull resistance; the aerodynamic model computes the rig forces; the equilibrium routine determines the imbalance between the rig driving force and the hull resistance, and the imbalance between the rig heeling moment and the hull restoring moment.

The optimizing routine adjusts the sail setting parameters, REEF and FLAT, to obtain the maximum possible value of VS (or VMG) for the given conditions. It could be said to perform the function of the crew and skipper in adjusting the boat parameters to optimize boat speed.

For a fixed course angle with respect to the true wind (BTW), and for a given true wind speed (VT), the VPP does the following:

1. Sets an initial guess as to the available variables.
The optimizing routine then takes over. For a fixed course and wind speed the variables available are:

VS Boat Speed
PHI Heel Angle
REEF Reefing Parameter
FLAT Flattening Parameter
LE Longitudinal Equilibrium error

RE Heeling Moment Equilibrium Error

2. Optimizes the boat speed, VS.

The optimizer is a Newton-Raphson routine to solve the following two equations:

RE = 0 (Roll Moment Balance)
LE = 0 (Longitudinal Force Balance)

and seek a solution such that VS is a maximum.

The condition for a maximum of VS is that the partial derivatives of VS with respect to the independant variables REEF and FLAT must equal zero. PHI is an implicit function of the remaining variables.

The details of the optimizer are not given here, since it is a relatively long and complicated program segment. Specific controls on the Newton-Raphson iteration scheme are imposed to assure convergence to a maximum (rather than a minimum) and to deal with the discontinuity in derivative definition when REEF or FLAT are in the neighborhood of their maximum values of unity.

To obtain the values of the various derivatives needed by the optimizer, repeated calls are made to a program segment which models the aerodynamic and hydrodynamic forces and moments and returns values of the imbalances RE and LE. The Newton-Raphson iteration scheme returns new values of the variables, closer to the desired value, and is repeated until the changes are less than some preassigned value. Typically the process converges to within less than .0001 knot in VS in from two to eight iterations.

For computing the optimum upwind and optimum downwind conditions, the sailing angle, BTW is made an independent variable, and the speed made good, VS*COS(BTW) is maximized.

------------ HYDRODYNAMIC MODEL ----------------

The hydrodynamic model uses LPP inputs to compute the forces and moments on the hull needed for computing the equilibrium between the aerodynamic forces on the rig and the water forces on the hull.

The hull restoring moment is computed for comparison to the aerodynamic heeling moment induced by the rig, and the resistance of the hull is computed for comparison to the driving force on the rig.

RESTORING MOMENT:

The restoring moment (RM) is calculated by:

RM = (RM2 + (4./3.*RM20-5./4.*RM2-RM40/12.)*(PHI/20.)^2 +
(RM40/12.-RM20/3.+RM2/4.)*(PHI/20.)^4 + RMV*SLR) * PHI

RMAUG = RM6*COS(PHI)

IF (ABS(PHI).LT.6.) RMAUG = RMAUG * SIN(15.*ABS(PHI))^2

RM = RM + RMAUG * SIGN(PHI)

Where PHI = Heel Angle in degrees
RM2 = (Restoring Moment at 2 degrees)/2
RM20 = (Restoring Moment at 20 degrees)/20
RM40 = (Restoring Moment at 40 degrees)/40
RM6 = (Restoring Moment due to crew weight)
CARM = .475*BMAX-1 (Crew Moment Arm)
BMAX = Maximum Beam (from LPP)
SLR = VS/SQRT(LSM) (In knots and feet)

CREWRW = (.27*LSM-1.33)*170. (IMS movable crew weight)
IF (LSM.LE.16.) CREWRW= (.375*LSM1-3.)*170.

RM6 = CARM*CREWRW

RMV = 5.955E-5 * DISPL * LSM * (1. - 6.25*(MHSB/SQRT(AMX) - 2.1))

DISPL = Displacement in sailing trim
AMX = Area of maximum section in sailing trim
LSM = Second Moment Length in sailing trim

Note 1: The IMS total crew weight is given by:

CW = (.375*LSM - 3.)*170

and for boats longer than 16 ft. LSM, only the fraction given above as CREWRW is considered movable.

Note 2: RMAUG is to assure a smooth transition of the crew augmented stability from zero at zero degrees heel to the full value of the crew moment on the rail at heel angles above six degrees.

Note 3: RMV is a term intended to represent the change in restoring moment due to boat speed, and was derived from the Delft series experiments.

HEELING MOMENT:

The VPP heeling moment is calculated by:

HM = HMA + RM4*FHW

where HMA is the heeling moment of the rig, and the second term represents the heeling moment of the hull keel combination.

DEF = Effective draft of keel or keel-centerboard
RM4 = .43*DEF
FHW = Total Heeling Force

DEF is computed from the following equations:

XXB = SQRT(4.*CBSA/(PI*MHSBTR)
ECE = ECMA*TANH(SQRT(ECMA/(DHKA-XXB))/2. + .2*(ECMA/(DHKA-XXB))^2)
DEF = DHKA + ECE

(NOTE : If there is no centerboard, DEF = DHK.
See rule book for definition of ECMA, DHKA, ECE, CBSA.
XXB = Surrogate Hull Depth at Centerboard Location.
CBSA = Hull Section Immersed Area at C.B. Location.)

LONGITUDINAL FORCE EQUILIBRIUM:

The hydrodynamic resistance of the hull is computed from:

FRW = DUR + DI + DH + DRU

Where FRW is the resistance force of the water
DUR is the upright resistance
DI is the induced resistance due to sideforce on the hull
DH is added resistance due to heel of the hull
DRU is a term to add resistance when the rail goes under

DUR is computed from a correlation derived from the Delft Tank Model experiments, supplemented by data from other sources. DUR is the sum of the wave making resistance, RW, and the skin friction drag RF.

RF = CSfT*QW*WS

where:

CSfT = Skin Friction Coefficient

WS = Wetted Surface of Hull and Appendages
QW = Dynamic Pressure of Water (.5*Rho*VS^2)
CSfT = 0.075/[LOGS10T(Re)-2]^2

Re = Reynolds No

RW = A1*(BTR)^A2*Cv/(SQRT(Cv^2+A3)*DISP*10^(-5)

and the values of the A's are given in the following table

VS/SQRT(LSM) A1A2A3

0.414.2 .120
0.649.4 .190
0.8 107.3 .290
1.0 241.9 .260
1.2 611.5 .190
1.4 2427.6 .0859
1.6 7421.8 .04649

1.8 14055.0 .03264

DH = DUR*(.0032*(1.015 -LSM3/LSM1)*PHI^2

DRU = .0004*(PHI - 30)^2

DI = FHW^2/IMSD^2/QW

where FHW is the Heeling Force on the rig, IMSD is the reduced draft computed by the LPP (see below) and QW is the dynamic pressure.

AERODYNAMIC FORCES:

The driving and heeling forces on the rig, are computed from a model of the sail aerodynamics, using the apparent wind speed and apparent wind angle computed at the rig center of effort.

To account for the wind gradient, the true wind at the center of effort of the rig is computed by:

VTW = 0.1086*VT*LOG(3048.8*ZCE) (Units feet and knots)

where ZCE is the height of the center of effort of the rig, corrected for reefing and heel angle by:

ZCE = Z0*REEF*COS(PHI)

and VT is the true wind velocity at a nominal height of 10 meters, and Z0 is the center of effort height for the rig computed by the aerodynamic model.

The apparent wind at the center of effort is then computed by:

VAW = SQRT[(VTW*SIN(BTW)*COS(PHI))^2+(VTW*COS(BTW) + VS)^2]

And the apparent wind angle at the center of effort is given by:

BAW = ATN{VTW*SIN(BTW)*COS(PHI)/(VTW*COS(BTW) + VS)}

The aerodynamic forces acting on the boat are computed by:

FRA = SFACT * VASQ * CR
FHA = SFACT * VASQ * CH
HMA = SFACT*VASQ * ((HBI+ZCEB*REEF)*(CH-SINB*CD0) + ZWNDG*SINB*CD0)

where
FRA = Aerodynamic Driving Force

FHA = Aerodynamic Heeling Force
HMA = Aerodynamic Heeling Moment
SFACT = SA * 3.380074E-3 (For VAW in Knots,SA in feet^2)
VASQ = VAW^2
CR = CLB*SIN(BAW) - CDB*COS(BAW)
CH = CLB*COS(BAW) + CDB*SIN(BAW)
CLB = Lift Coefficient of Sails,Hull,and Rig at BAW
CDB = Drag Coefficient of Sails,Hull,and Rig at BAW
CR = Driving Force Coefficient
CH = Heeling Force Coefficient
HBI = Height of Base of I
ZCEB = Height of Rig Center of Effort above HBI
ZWNDG = Center of Effort of Windage Drag above DWL
CD0 = 1.13*AP/SA
ZCE0 = .4*EHM
ZWNDG = HBI + ZCE0
AP = FBAV*IMSB + EDMC*EHM + EDY*EHY
AP = Parasite Drag Area of Hull and Rig
SA = Reference Sail Area

Note : for undefined variables see rule book.

EQUILIBRIUM ERRORS:

The Longitudinal And Heeling Equilibrium Errors used in the optimizer are given by:

LE = FRA - FRW
RE = HM - RM

----------- SAIL AERODYNAMIC MODEL ------------

The sail model used by the VPP derives estimates of the sail forces from IOR Rig Measurements. Here we outline the methodology and give the main algorithms employed for jib-headed sloops, yawls, and ketches. (Schooner rigs and gaff rigged cases are also treated by the VPP, and the reader is referred to the program listings for the details, as well as particulars of the array storage schemes used, etc.)

The principal rig dimensions measured under the IOR are:

SPL Spinnaker Pole Length
SMW Spinnaker Maximum Width
SL Spinnaker Luff/Leach Length
IHeight of Fore Triangle
JBase of Fore Triangle
LPG Longest Perpendicular of Largest Jib
PMainsail Hoist
PC Ditto Corrected
EFoot of Mainsail
EC Ditto Corrected
BAS Boom Above Sheer
MGU Mainsail Upper Girth
MGM Mainsail Mid Girth
HB Headboard of Mainsail

FSP Forestay Perpendicular

for yawls and ketches

PY Mizzen Hoist
PYC Ditto Corrected
EY Foot of Mizzen
EYC Ditto Corrected
BADY Mizzen Boom above sheer
EB Distance Between Masts
YSF Mizzen Staysail Foot
YSD Mizzen Staysail Depth
YSMG Mizzen Staysail Mid Girth

In addition to the measurements above, the IMS uses the following mast measurements to estimate the windage effects of the masts on performance:

MDL1 Maximum Long. Dimension of Mainmast
MDL2 Long. Dim. of Mast at Head
MDT1 Maximum Thickness of Mainmast
MDT2 Thickness of Mainmast at Head
TL Taper Length of Mainmast

and similar measurements for the mizzen mast, MDL1Y, MDL2Y, etc.

SAIL AREAS AND HEIGHTS:

The IMS computes the areas and center of effort heights of the several sail types as follows:

Spinnakers:
AS =.6*SL*SMW
ZS = .59*I
Jibs:
AJ = SQRT(I^2+J^2)*(LPG+FSP)/2.

Mainsails:
IF(MGU .LT. ME/4.) MGU = ME/4.
IF(MGM .LT. ME/2.) MGM = ME/2.
AM = (PC/2.* (ME+MGM)/2.+ PC/4. * (MGM+MGU)/2. + PC/4. * MGU/2.)/1.16
ZM = .39*PC + MBAD(should use P not PC)

Mizzen Staysails:
AYS = YSD*(2.*YSMG+YSF)/4.
ZYS = .39*(PYC+BADY) + (HBIY-HBI) (should use PY not PYC)

Mizzens:
AY = PYC*EYC/2.(should use PY not PYC)
ZY = .39*PYC + BADY + (HBIY-HBI) (should use PY not PYC)

A reference area (AN) for aerodynamic coefficients is computed as follows:
AF = I*J/2.
AN = AF+AM+AY

Formulas for mast heights, etc.

EHM = MAX(P+BAD,H+BAD,I)

EHY = MAX(PYC+BADY, MHY+BADY)(should use PY not PYC)
EDM = (.5*(EHM-TL)*(MDT1+MDL1) + .25*TL*(MDT2+MDL2+MDT1+MDL1)) / EHM
EDY = (.5*(EHY-TLY)*(MDT1Y+MDL1Y)+.25*TLY*(MDT2Y+MDL2Y+MDT1Y+MDL1Y))/EHY
EDMB =.0001*I*(LSM+95.)
EDMC = EDM
IF (EDM.LTDMB) EDMC = 4.*EDM*(EDM/EDMB)/(3.+(EDM/EDMB)^4)
AP = FBAV*IMSB + EDMC*EHM + EDY*EHY (Parasite drag area of hull + rig)
EHMX = AMAX1(EHM+HBI, EHY+HBIY)
MGAP = 2.*EB / (EHM+EHY)

AERODYNAMIC COEFFICIENT MODEL:

The aerodynamic coefficients for the rig are estimated from wind tunnel tests on two-dimensional sails.

For each sail type, spinnaker, jib, or mainsail a set of section lift and drag coefficients was chosen, defined as a function of the apparent wind angle, BAW:

/28.,41.,46.,60.,75.,100.,130.,150.,180./ Spinnaker BAW
/0.,1.31,1.56,1.71,1.69,1.4,.83,.5,0./ CLS
/.1,.15,.2,.4,.7,1.,1.10,1.10,1.10/CDS

/7.,15.,20.,27.,50.,60.,100.,150.,180./ Jib BAW
/0.,1.,1.375,1.45,1.43,1.25,.4,0.,-.1/ CLJ
/.05,.023,.031,.037,.25,.35,.73,.95,.9/ CDJ

/0.,7.,9.,12.,60.,90.,120.,150.,180./Main BAW
/0.,1.,1.22,1.35,1.25,.96,.58,.25,-.1/ CLM
/.05,.03,.027,.027,.114,.306,.671,1.11,1.2/ CDM

Section separation drag coefficients were chosen as follows:

KPS = .019
KPJ = .016
KPM = .016

Center of effort height coefficients were chosen as follows:

CES = .565
CEJ = .39
CEM = .39

Cubic splines are then fitted to the section lift and drag coefficients for the several sail types, to define the values at intermediate angles, and stored in arrays covering the range of BAW through 180 degrees.

The individual sail values are then used to compute an overall set of coefficients for the rig. The blanketing of one sail by another is taken into account. What follows is an extract of the VPP algorithms employed for this purpose.

Before summing the sail coefficients, the blanketing functions and aspect ratio correction terms are needed. The following are the principal algorithms employed:

AREA FRACTIONS:

Area fractions as follows are computed, for use in the blanketing formulae:

FJ = (AJ - MIN(AJ,AF)) / AJ
FS = AMIN1(AM/AS, 1.-1.488*MSPL/MSMW)
FM = AYS / AM
FYS = AY / AYS
FE = AMIN1(1., AJ/AF)

The blanketing functions are as follows for the upwind rig case:

Jib:
BKTJ = 1.
IF BAW IS GREATER THAN OR = 135 THEN BKTJ = 1 - FJ*((BAW-135)/45.)^2

Main:

IF BAW IS LESS THAN 90 THEN BKTM = 1

IF BAW IS GREATER THAN OR = 90 THEN
X = (BAW-135)/45
BKTM = 1-FM*(1+1.5*X+.5*X^3)/2
END IF

Mizzen Staysail:

IF BAW IS LESS THAN 45 THEN BKTYS = 0
(No Mizzen Staysail set below 45 degrees)
IF BAW IS GREATER THAN 60 AND BAW IS LESS THAN 90 THEN BKTYS = 1

IF BAW IS GREATER THAN OR = 90 THEN
X = (BAW-135)/45.
BKTYS = 1. - FYS*(1.+1.5*X-.5*X^3)/2.
END IF

IF BAW IS LESS THAN 60 AND BAW IS GREATER THAN 45 THEN
BKTYS = 1. - ((60-BAW)/15.)^2
END IF

FRACTIONAL RIG EXPOSED MAST FUNCTIONS:

For fractional rigs, the model recognizes that the portion of the main above the top of I is affected adversely by the presence of the mast, and takes this into account as follows:

SMD is a factor used to increase the drag of the mainsail for fractional rigs for apparent wind angles below 90 degrees.

SPOILER = MP+MBAD - MI(Exposed mast length above I)
SPOILAREA = (SPOILER/MP)^2

DFCT = 1. + 2.*SPOILAREA + 1.13*SPOILER*EDM/AM/CDM

```
IF (BAW.LT.90) GO TO 100
SMD = 1.
GO TO 900
 100IF (BAW.GE.40) GO TO 200
SMD = DFCT
GO TO 900
 200CONTINUE
```

```
X = ((65-BAW)/25.)^3 / 2. + .5
SMD = X*DFCT + (1.-X)
 900CONTINUE
RETURN
```

SML is a factor to reduce the lift on the exposed portion of the mainsail, computed as follows:

```
SML = 1. - .5*SPOILAREA
if downwind rig then SML = 1
```

JIB ENDPLATE FUNCTION:

To account for the reduction in effective aspect ratio of the rig when the jib is eased, opening a gap between the foot and the deck, we define an endplate factor BEND:

```
 IF BAW IS LESS THAN 30 THEN BEND = FE (FE is defined in area ratios above)
IF BAW = OR IS GREATER THAN 30 AND BAW IS LESS THAN OR = 90
THEN X = (BAW-60)/30
BEND = (1. 1.5*X +.5*X^3)*FE/2
END IF
IF BAW IS GREATER THAN 90 THEN BEND = 0
```

EFFECTIVE ASPECT RATIO FOR SPLIT RIGS:

The effective aspect ratio for split rigs uses the following algorithm for computing the effects of span ratio and gap, derived from biplane theory:

```
FUNCTION SIGMA(MU,GAP)
DATA T/1., .785, .665, .57, .49, .425, .375, .33, .295, .265, .24,
1.8, .69, .6, .525, .46, .4, .355, .315, .28, .25, .225,
2.6, .54, .485, .435, .39, .355, .32, .285, .26, .235, .21/

IG = MAX0(MIN0(INT(GAP/.05), 9), 0)
IM = MAX0(MIN0(INT((1.-MU)/.2), 1), 0)
IGP = IG+1
IMP = IM+1

GS = GAP/.05 - IG
MS = (1.-MU)/.2 - IM
GSI = 1.-GS
MSI = 1.-MS

SIGMA = MSI*GSI*T(IG,IM) + MSI*GS*T(IGP,IM) + MS*GSI*T(IG,IMP) +
1MS*GS*T(IGP,IMP)
RETURN
```

SUMMATION OF INDIVIDUAL SAIL CONTRIBUTIONS:

Individual sail contributions to the rig lift and drag are summed for each of the two rig configurations, upwind (jib, mainsail, mizzen staysail and mizzen) and downwind (spinnaker, main, mizzen staysail, and mizzen), and stored in arrays as a function of BAW.

The summation formulae are as follows:

UPWIND CASE

CL1 = CLJ*BKTJ*AJ + CLM*BKTM*AM*SML
CL2 = CLJ*BKTYS*AYS + CLM*AY

CL = CL1 + CL2(Total Lift Factor)
CDP = CDJ*BKTJ*AJ + CDM*BKTM*AM*SMD + CDJ*BKTYS*AYS + CDM*AY
(Total Parasite Drag Factor)
FCDJ = CDJ(36)*BKTJ(36)*AJ/CDP(36) (Jib Drag Ratio)

CFJ = SQRT(CLJ^2 + CDJ^2) (Jib Resultant)
CFM = SQRT(CLM^2 + CDM^2) (Main Resultant)
CFYS = SQRT(CLJ^2+CDJ^2)(Mizzen Staysail Resultant)
CFY = CFM(Mizzen Resultant)
CF = SQRT(CL^2 + CDP^2) (Total resultant coefficient)

ZCE = (CFJ*BKTJ*AJ*ZJ + CFM*BKTM*AM*ZM + CFY*AY*ZY)/CF (Rig CE. height)

KPP = CLJ^2*BKTJ*AJ*KPJ + CLM^2*BKTM*AM*KPM + CLM^2*AY*KPM
KPP = KPP * AN / CL^2 (Separation drag term)_

EMARF = 1.(Equivalent monoplane aspect ratio factor)

IF (NOTSPLIT RIG) GO TO 600
XR = CL1/CL2(Lift Ratio for split rigs)
MU = EHM/EHY(Span Ratio for split rigs)
GAP = SIN(BAW) * MGAP (Effective Gap)
EMARF = (MU*(1+XR))^2 / (MU^2 + 2.*SIGMA(MU,GAP)*MU*XR + XR^2)
600CONTINUE

B1 = EHMX*(1.+.1*BEND)(Effective rig height)
AR = EMARF * B1^2 / AN(Equivalent monoplane aspect ratio)
CE(BAW) = KPP + 1./(3.14159*EMAR) (Induced drag factor)

CL = CL/AN(Normalized Total Lift Coefficient)
CDP = CDP/AN(Normalized Parasite Drag Coefficient)
800CONTINUE

CD0 = 1.13*AP/AN (Parasite Drag Coefficient of Hull + rig)
ZCE0 = .4*EHM (CE. Height of Parasite Drag above HBI)
ZWNDG = HBI + ZCE0 (CE. Height of Parasite Drag above DWL)
SA = AN(Reference Sail Area)

DOWNWIND CASE

The downwind rig aerodynamics are handled in a similar fashion, with the spinnaker replacing the jib.

The blanketing functions for the downwind case are:

Spinnaker:

IF BAW IS LESS THAN 135 THEN BKTS = 1.
IF BAW IS GREATER THAN OR = 135 THEN BKTS = 1. - FS*((BAW-135)/45.)^2

Main:

IF BAW IS LESS THAN 90 THEN BKTM = 1
IF BAW IS GREATER THAN OR EQUALS 90 THEN
X = (BAW-135)/45
BKTM = 1-FM*(1+1.5*X+.5*X^3)/2
END IF

Mizzen Staysail:

IF BAW IS LESS THAN 45 THEN BKTYS = 0
(No Mizzen Staysail set below 45 degrees)
IF BAW IS GREATER THAN 60 AND BAW IS LESS THAN 90 THEN BKTYS = 1

IF BAW IS GREATER THAN OR EQUALS 90 THEN
X = (BAW-135)/45.
BKTYS = 1. - FYS*(1.+1.5*X-.5*X^3)/2.
END IF

IF BAW IS LESS THAN 60 AND BAW IS GREATER THAN 45 THEN
BKTYS = 1. - ((60-BAW)/15.)^2
END IF

And the aerodynamic coefficients are computed by:

CL1 = CLS*AS + CLM*BKTM*AM*SML
CL2 = CLJ * BKTYS*AYS + CLM*AY
CL = CL1+CL2

CDP = CDS*AS + CDM*BKTM*AM*SMD + CDJ*BKTYS*AYS+ XCDM*AY

CFS = SQRT(CLS^2 + CDS^2)
CFM = SQRT(CLM^2 + CDM^2)
CFYS = SQRT(CLJ^2+CDJ^2)
CFY = CFM
CF = SQRT(CL^2 + CDP^2)

ZCE = (CFS*AS*ZS + CFM*BKTM*AM*ZM +
CFYS*BKTYS*AYS*ZYS + CFY*AY*ZY) / CF

KPP = CLS^2*BKTS*AS*KPS + CLM^2*BKTM*AM*KPM +
CLJ^2*BKTYS*AYS*KPYS + CLM^2*AY*KPM

KPP = KPP * AN / CL^2

EMARF= 1.
IF (NOT SPLIT RIG) GO TO 600

XR = CL1/CL2 (Lift Ratio for split rigs)
MU = EHM/EHY (Height Ratio for split rigs)
GAP = DSIN(I/DEGRAD) * MXGAP
EMARF = (MU*(1+XR))^2 / (MU^2 + 2.*SIG(MU,GAP)*MU*XR + XR^2)
600CONTINUE

EMAR = EMARF * EHMX^2 / AN

CE = KPP + 1./(3.14159*EMAR)

CL = CL/AN
CDP = CDP/AN

CD0 = 1.13*AP/AN
ZCE0 = .4*EHM
ZWNDG = HBI + ZCE0
SA = AN

COMPUTATION OF FORCES AND MOMENTS:

The algorithms given above provide the basis for calculation of the aerodynamic and hydrodynamic forces and moments acting on the boat.

The VPP also includes appropriate algorithms for dealing with schooner rigs and gaff headed sails. The reader is referred to the program for details.

The aerodynamic coefficients, including the effects of reefing and flattening are computed by:

CLB = CL * REEF^2 * FLAT
CEB = CE *CL^2

CDPB = CDP

CDB = CD0 + CDPB * (FLAT*FCDJ + (1-FCDJ)) * REEF^2 + CEB*FLAT^2*REEF^2
(Note for downwind rig case FCDJ = 0)

ZCEB = ZCE

Finally, the driving and heeling forces, and the heeling moment are computed by equations given above, repeated here for convenience:

CR = CLB*SIN(BAW) - CDB*COS(BAW) (Driving force coefficient)
CH = CLB*COS(BAW) + CDB*SIN(BAW) (Heeling force coefficient)

FRA = SFACT * VASQ * CR(Driving force)
FHA = SFACT * VASQ * CH(Heeling force)
HMA = SFACT*VASQ * ((HBI+ZCEB*REEF)*(CH-SINB*CD0) + ZWNDG*SINB*CD0)
(Heeling moment)

Q = (RHO*VAW^2)/2 Dynamic Pressure in consistent units

SFACT = Q*SA/VAW^2 = RHO*SA/VAW^2 (For consistent units)
SFACT = SA * 3.380074E-3 (For VAW in Knots,SA in feet^2)

VAW = SQRT[(VTW*SIN(BTW)*COS(PHI))^2+(VTW*COS(BTW) + VS)^2]
VASQ = VAW^2
BAW = ATN{VTW*SIN(BTW)*COS(PHI)/(VTW*COS(BTW) + VS)}

COMPUTATION OF BOAT SPEEDS:

The algorithms summarized so far describe the aerodynamic and hydrodynamic representation (boat model) of the boat for the purpose of speed estimation. Boat speeds for a large number of cases are calculated, using the boat model, and the optimizer routine. The conditions currently calculated are as follows:

True Wind SpeedsVT = 8,10,12,14,16,20 knots

True Wind Angles For Upwind Rig:
BTW = 36,44,52,60,70,80,90,110,120,135,150,165,180
and BTW for optimum VMG both upwind and downwind

True Wind Angles For Downwind Rig:
BTW = 60,70,80,90,110,120,135,150,165,180
and BTW for optimum VMG downwind.

For each condition, the VPP computes boat speed, heel angle, and REEF and FLAT, as well as the forces and moments at equilibrium. The results are used in preparation of certificates and performance packages.

CERTIFICATE DATA:

The IMS certificate tabulates predicted boat speeds, and predicted heel angle for each of the true wind speeds, for the following selected courses:

Optimum Beat, optimum run, BTW = 80, 110, 135 and 180 degrees.

Optimum Beat speed is for upwind rig, optimum run for downwind rig, and for the reaching courses of 80 and 110 degrees, the reported speed is for whichever rig, upwind or downwind, results in the higher speed.

In addition, the certificate provides predicted times for 5 specified course types, Windward-Leeward, Olympic, Circular Random, Linear Random, and Linear Random non-spinnaker.

The Windward-Leeward times are in seconds/mile for a course of equal legs directly upwind and directly downwind.

The Olympic times are for a six leg Olympic course, consisting of one leg directly upwind, one reach at 135 degrees to a side mark half way between the downwind and upwind marks offset by half the distance between the marks, one reaching leg to the downwind mark, a beat to the upwind mark, a run to the downwind mark, and a final beat to the upwind mark.

The linear random and circular random courses are for use in races from point to point, and are based on two different assumptions about the wind pattern.

Circular random times are computed on the basis that the wind blows always from the same direction, and that the boat sails equal distances on all courses from dead upwind to dead downwind - as if required to circumnavigate a circular island. These times may be useful for closed courses around government marks.

Linear random times are computed on the basis that the boat sails in a straight line from point to point, and the wind blows for equal times from all directions from 0 to 180 degrees with respect to the course. These times are useful for port to port races and around the buoys races in which no substantial dead upwind or dead downwind content is expected.

The VPP calculates circular random and linear random times by first fitting the speeds as a function of BTW by a cubic spline for all angles between optimum upwind and optimum downwind. (For reaching courses, the greater of the speeds for upwind or downwind rig is used.) The end conditions on the spline are given by the requirement that dVMG/dBTW = 0 at the end points.

For directions between optimum upwind and dead to weather, the speed is given analytically by:

VS(BTW) = VMGU/COS(BTW)

Similarly, between optimum downwind and 180 degrees,

VS(BTW) = VMGD/COS(BTW)

The resultant polar diagram of VS(BTW) is then used to compute the two times in seconds/mile.

Circular random inverse speed in seconds/mile is then given by the integral from 0 to 180 degrees of 3600/VS divided by 180.

Linear random inverse speed is simply 3600 divided by the integral of VS(BTW) from 0 to 180 degrees divided by 180.

The non-spinnaker times are reported for linear random courses using the upwind rig, and are useful for cruising canvas races.

PERFORMANCE PACKAGE:

For owners who desire more information about the predicted performance of their boat than appears on the certificate, a performance package can be had from the National Authority. This package includes polar diagrams for several wind speeds, and a more complete print out of the speed predictions. Owners have found this package of great value in tuning their boats up in preparation for racing.

Historical remarks:

The VPP was originally written by a group at MIT, under the

Pratt Project. The most complete description of the program available is MIT Pratt Project Report 78-11, which should be read by anyone seriously interested in the program development.

Since that report was published in 1978, some substantial changes have been made in the program, under the general direction of the USYRU MHS Committee.

Perhaps the most significant change was in the treatment of the rig aerodynamics. The original aerodynamic model, described in 78-11, was appropriate only for sloops with rig proportions similar to those of the yacht BAYBEA, on which sailing experiments had been made to determine the aerodynamic forces. In 1979 and 1980 the aerodynamic treatment was completely revised, to permit taking into account varying rig proportions, and to provide reasonable estimates of the forces on split rigs (yawls, ketches and schooners).

The current aerodynamics model was developed by George Hazen, following suggestions by the author and Karl Kirkman. It is as described above, and is based on aerodynamic theory together with wind tunnel tests on two dimensional sails.

The hydrodynamic model was also changed, principally because the effects of changes in BTR in the original model appeared too great compared to observed results of races.

Finally, the optimizing routine was changed from a relatively slow successive approximation method to the current multiple degree of freedom Newton-Raphson method, following suggestions by John Letcher, George Hazen, and the author. The new method is considerably faster and no less accurate than the original scheme.

For details of the hydrodynamic model changes, see the following section of this appendix dealing with the LPP program.

LPP ALGORITHM SUMMARY

The LPP (Lines Processing Program) of the IMS provides input data for the VPP derived from machine measurements of the hull.

This report provides generalized information only. The LPP is a complicated, long, specialized hydrostatic program. We hope only to give enough information so that an experienced programmer, with naval architecture background, could reproduce the results, and so that an interested yacht owner could learn the general approach taken.

The VPP requires the following hull inputs:

LSM1 (sailing trim 0 degrees heel)
LSM2 (sailing trim 2 degrees heel)
LSM3 (sailing trim 25 degrees heel)
LSM4 (sunk trim)
DISPL Sailing trim displacement

AMS1 Maximum underwater section area
B IMS Beam
BTR IMS beam-draft ratio
DHK Keel draft
ECM Centerboard extension
WSWetted surface, sailing trim
PIPA Propeller Installation Projected Area
DHKA Adjusted Depth of hull-keel combination
ECMA Adjusted centerboard extension
CBSA Immersed area at centerboard maximum depth
BMAX Maximum beam (taken from offsets)
RM2 Righting moment per degree at 2 degrees heel
RM20 Righting moment per degree at 20 degrees heel
RM40 Righting moment per degree at 40 degrees heel
FBAV (.625*FF + .375*FA)
HBI Freeboard at base of I in sailing trim
HBIY Freeboard at base of IY in sailing trim
L (.3194*[LSM1+LSM2+LSM4])

GENERAL REMARKS ON LPP:

The heart of the LPP is a hydrostatic program which accepts offset data defining the hull shape from the measurement machine results processed by the LAP, and generates hull data required by the VPP. In addition to the the offset table, inclining measurement results, fore and aft girth station locations, freeboard measurements in measurement trim, and propeller installation data are required. These data are provided by the measurer.

The IMS hull measurements, taken by measurement machine, are sufficient to define the shape of the hull completely. The LPP performs two functions. Firstly it uses the flotation and inclining measurements to determine the weight of the boat and the longitudinal and vertical center of gravity location in measurement trim. It then can compute the flotation plane in sailing trim and the restoring moment as a function of heel angle in sailing trim. These calculations are performed by a straightforward hydrostatic program which need not be described here.

For estimation of the hull drag as a function of boat speed and heel angle, the most important dimensions are the displacement, the wetted surface, and length dimensions to characterize the size and shape of the boat.

Rather than using point measurements such as LWL, BWL, etc. to characterize the boat, the IMS employs lengths determined by integrating over the entire underwater part of the hull.

The VPP hydrodynamic resistance model requires the following hull characteristics in sailing trim:

L .3194*(LSM1+LSM2+LSM4)
DISP Displacement
LSM3 LSM heeled 25 degrees
BTR Integrated Beam/Depth ratio
AMS1 Maximum Immersed Section Area
DHK Maximum Draft of Hull Keel Combination
RM2 Restoring Moment per Degree at 2 Degrees Heel

RM20 Restoring Moment per Degree at 20 Degrees Heel
RM40 Restoring Moment per Degree at 40 Degrees Heel

(For centerboard boats the VPP requires in addition ECM, ECMA, KCDA, DHKA, and CBSA. See rule book for definitions)

As a result of the Pratt Project analysis of the Delft Series model tests, it was determined that the linear combination of LSMs given above serves well as a measure of effective length.

The second function of the LPP, then, is the calculation of the integrated hull characteristics for resistance estimation.

We now consider the calculation of the several LSMs.

The general definition of LSM (second moment length) is given by:

LSM = 4.26*SQRT{(M1/M2) -(M3/M2)^2}
M1 = xS2TsS1/2Tdx
M2 = sS1/2Tdx
where s is the immersed sectional area attenuated for depth at the length location x and the integrations are performed over all x under water.

The depth attenuation factor applied to underwater offsets to calculate attenuated section areas is:

eS-10z/LSM0T

Where LSMO the LSM in measurement trim.

(Since LSM0 depends on the attenuation factor, an iterative procedure is used to determine LSM0, starting with LBG as an approximate value of LSM0)

LPP PROGRAM SUMMARY:

Here we summarize the principal steps of the LPP, together with the VPP inputs derived from each step.

Step 1: Measurement Trim, zero degrees heel.

The first step in the LPP is computation of measurement trim conditions. From the freeboard measurements the flotation plane is known, and the hydrostatic program integrates the offset data below the waterline plane to determine the displacement, the fore and aft location of the center of bouyancy, and LSM0.

OUTPUTS FROM STEP 1:

LSM0
DISP in measurement trim
LCB in measurement trim

In this step the righting moment per degree is also calculated for the cg. at the waterplane, in order to permit computation of the vertical cg. location in step 2.

Step 2: Measurement trim , 2 degrees heel:

From the inclining measurement, the restoring moment per degree for small angles of inclination is known. The LPP uses this measurement, together with the hydrostatic data in measurement trim at 2 degrees of heel, to compute the vertical location of the center of gravity, needed later to compute restoring moments for input to the VPP.

OUTPUTS FROM STEP 2:

Vertical C.G. location, measurement trim

Step 3: Sailing Trim , 0 degrees heel.

In this step, the LPP adds the weight of crew, stores, and sails to the boat, and computes the equilibrium flotation for the boat in sailing trim.

The crew weight is taken to be:

CRWT = (.375*LSM0 - 3)*170 (in pounds)

And the gear weight is taken to be:

GWT = (0.1*LSM0)^2*30 (in pounds)

The sail weight is taken to be:

SWT = 27*(0.1*LSM0)^2 (in pounds)

The combined crew and gear weight are added to the boat at a longitudinal position 0.2*LSM0 aft of the longitudinal center of buoyancy determined in step 1 above and at a vertical location 0.05*LSM0 +1.2 feet above the plane of flotation in measurement trim.

The sail weight is added at a longitudinal position .08*LSM0 forward of LCB in measurement trim, and (.033*LSM0 - .3 feet) above the flotation plane in measurement trim.

The hydrostatic program now computes a new plane of flotation, corresponding to the boat in sailing trim.

In this step the wetted surface, LSM1, BTR, B, and IMSD are also computed. LSM is computed by the formula given above. Wetted surface is obtained by straightforward integration of the underwater girths along the submerged length of the hull. B and BTR are integrated values defined as follows:

B = 3.45 * SQR(A1(7)/A1(6))
T = 2.07 * AMS2/B
BTR = B/T

Where AMS2 is the largest value of the depth attenuated immersed area in sailing trim, zero degrees heel.

and A1(7) = bS3TeS-10/LSM0Tdzdx

A1(6) = beS-10/LSM0Tdzdx

where b is the local beam at z,x.

IMSD:

The reduced draft used for computing the induced drag for a keel boat is found from the following formulae, based upon a proposal by John Letcher for handling the hull-keel interference:

BEF(x) = SQRT(4.*SI(x)/(3.14159*BTR)) SI is local section area
Y(x) = DRAFT(x) Y is local keel draft
x is the longitudinal position of a measurement station

R1 = .5*(Y(x)/BEF(x) + SQRT((Y(x)/BEF(x))**2 + .25*BTR**2 - 1.))
R2 = SQRT(R1**2 - .5*(1. + .5*BTR))

TR = MAX(BEF(x)*(R2 - .25*(.25*BTR**2-1.)/R2))

IMSD = .92*TR

(For centerboard cases a similar calculation is performed, using the hull immersed area at the location of the centerboard maximum extension for SI(x) and the corrected draft (DHKA + ECMA) in place of Y(x).)

OUTPUTS FROM STEP 3:

LSM1
WS
B (IMS effective beam)
T (IMS effective depth)
BTR(IMS effective beam/depth ratio)
AMS1 (Maximum immersed section area)
DHK(Maximum Draft)
IMSD (Reduced Draft)

Step 4. Sailing trim, 2 degrees heel:

The hydrostatics program heels the boat (free to trim longitudinally) to 2 degrees, and computes the heeling moment and the LSM for this condition:

OUTPUTS FROM STEP 4:

RM2
LSM2

Step 5. Sailing trim, 20 degrees heel:

OUTPUT FROM STEP 5:
RMA20

Step 6. Sailing trim, 25 degrees heel:

The VPP requires the LSM at 25 degrees heel to estimate the effect of heel on hull resistance.

OUTPUT FROM STEP 6:
LSM3

Step 7. Sailing Trim, 40 degrees heel.

OUTPUT FROM STEP 7:
RM40

Steps 8 - 14, Sailing trim:

for heel angles of 60,90,120,150,and 165 degrees, the LPP computes the restoring moment for use in computing the range of positive stability , righting arms, and the ratio of the area under the positive stability curve to that under the negative stability curve. These values are given on the certificate, as a guide to the owner in deciding what weather conditions he may wish to face with his boat.

Step 15. Sunk Condition:

To provide an estimate of the effects of overhangs, an LSM is computed with the boat at zero degrees heel, sunk below the sailing trim condition by .025*LSM1 at the forward freeboard station and by .0375*LSM1 at the after freeboard station.

OUTPUT FROM STEP 15:
LSM4

DEFINITION OF L:

L = .3194 (LSM1 + LSM2 + LSM4)

Transom Corrections:

In the event that the after end of the waterline in any of the trim conditions intersects a transom, the LPP adds a "tail" to the boat, for computing the LSM. (Not for the hydrostatic equilibrium computations).

The "tail" extends the depth attenuated sectional area curve to a virtual point stern located at a distance of SQRT(2*SL) aft of the last station, where SL is the depth attenuated section area of the last station. The curve with the extension is used for the integrations given above for the several LSMs.

General remarks:

The hydrostatic program integrates each underwater section by joining the measurement points by straight lines in the plane of the section. Trim changes are handled by a coordinate transformation in which the vertical coordinates are changed by the change in freeboards, but the longitudinal coordinates are not altered. Thus, the hull is sheared when the trim differs from the trim in measurement flotation. The error committed by this approximation is, in practice, negligible.

Tests have been conducted by USYRU to determine the accuracy of the displacement calculated from machine hull measurements by weighing several boats immediately after the in water flotation measurements. The agreement was within the expected accuracy of the weighing experiments.

As the program is set up on the USYRU computer, a number of integral values, not now used in the VPP, are calculated. For example, for each condition the wetted surface is computed, although only the value for sailing trim is needed by the VPP. Other hull characteristics, e.g. prismatic coefficient, block coefficient, BTR, can also be obtained from the program for any of the flotation conditions. These values may prove useful in the future, as the VPP hydrodynamic model is developed further.

The LPP has been developed over many years. The main body of the program was written by MIT during the Pratt Project, as were the spline routines, and other program elements used for interpolations. The Pratt Project report 78-11 describes the VPP and LPP structure as of March 1978, and should be read by anyone interested in studying the programs.

Since that report, a few significant changes have been made. The LSM routines originally were based on the section area curves and now are based on depth attenuated section area curves. Some changes have recently been introduced to deal with boats whose area curves in the after end are affected by rudders behind the point of the after waterplane intersection. The method of modeling the inclined drag in the VPP has been changed, and the fit of the restoring moment in the VPP has been changed to make the fitting function consist only of odd order terms in PHI,as required by symmetry about the origin of PHI. This change dictated computation of RMs at 20 and 40 degrees. Finally, the method of computing the reduced draft has been changed, using the model of hull keel interaction developed by John Letcher, since the original MIT model was found to be unsuitable for broad, shallow hulls.

It can be expected that the LPP will be further modified with time. In particular, the definition of L is under active consideration by the ITC and may be revised in the near future, as new data to supplement the Delft Series tank test results are obtained.