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DOI: 10.1515/aon-2017-0012

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PROPOSITION OF IONOSPHERIC GRID IN NAVIGATION SATELLITE SYSTEM BEIDOU

ABSTRACT

This study shows the way of ionospheric data usage obtained from 2 Tables using D2 NAV message Chinese BeiDou system. It was identified particular algorithms for Table's calculation. Authors also suggested data Table 2 modification and special algorithms useful for that Table. It was given calculated examples for BeiDou system Tables as well as for new suggested system.

Keywords:
satellite navigation system, BeiDou system, ionospheric correction.

INTRODUCTION

In Publisher December 2013 article BDS-SIS-ICD — v. 2.0 (BeiDou system — Signal in Space — Interface Control Document v. 2.0) author suggested algorithm for calculation ionospheric correction use using D2 NAV information grid message about ionospheric status. That grid includes China and south-east part of Asia. It consists from 2 Tables dislocated in 2.5 degrees of latitude. Authors suggest cited interpolation algorithms which gives possibility to find vertical ionospheric delay value induced by ionospheric impact. In this work had written bit different interpolation algorithms of ionospheric delays and ionospheric grids.

IONOSPHERIC INFORMATION GRID

D1 and D2 messages are formulated and modulated. They have quite different structure. D1 NAV is modulated by 50 bit/s frequency code and D2 NAV by 500 bit/s frequency code. D1 NAV has navigation basic information, almanac all satellites of BeiDou system and delay times of other systems. D2 NAV concerns only GEO satellites, their basic information and service support (BDS integration, difference correction service and ionospheric grid information).

Ionospheric grid information consist of the $d\tau$ vertical delay at grid point delays and its error index (GIVEI — Grid point Ionospheric Vertical delay Error Index). Data description and their capacity are shown in Table 1.

Tab. 1. Data description and their capacity

Parameter	$d\tau$	GIVEI
No. of bits	9	4

The Frame structure in format D2 is shown in Figure 1.

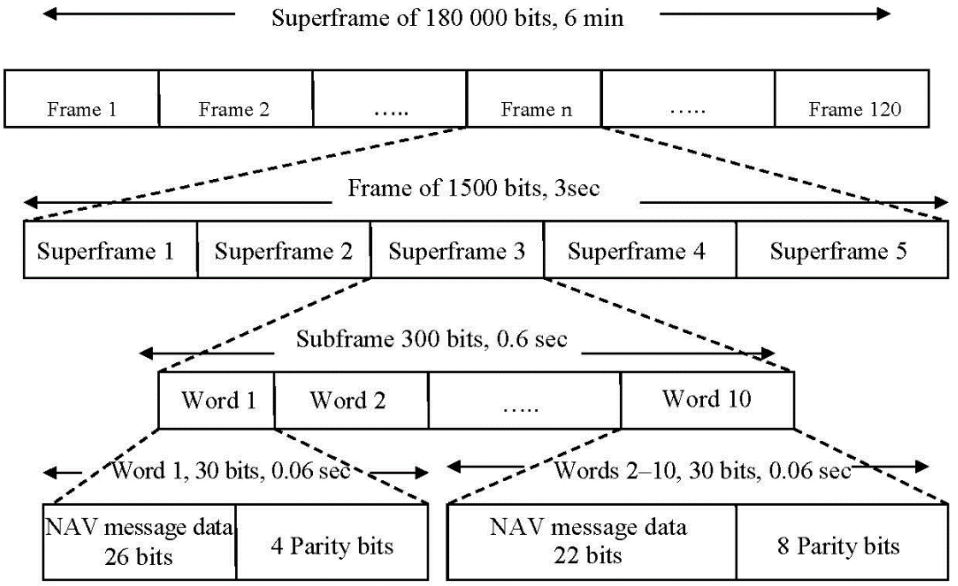

Fig 1. Structure of NAV message in format D2

D2 NAV message is build with superframe, frames and subframes. Each superframe has 180 000 bits continues 6 minutes. It consists from 120 frames includes 1500 bits per 3 seconds. Each frame has 5 sub frames (300 bits per 0.6 s). Each subframe has 10 words (30 bits per 0.06 s.). Information in format D2 includes: the basic NAV information of the broadcasting satellite, almanac, time offset from other systems, integrity and differential correction information of BDS and ionospheric grid information as shown in Figure 2 [BeiDou Navigation Satellite System, Signal in Space, Interface Control Document].

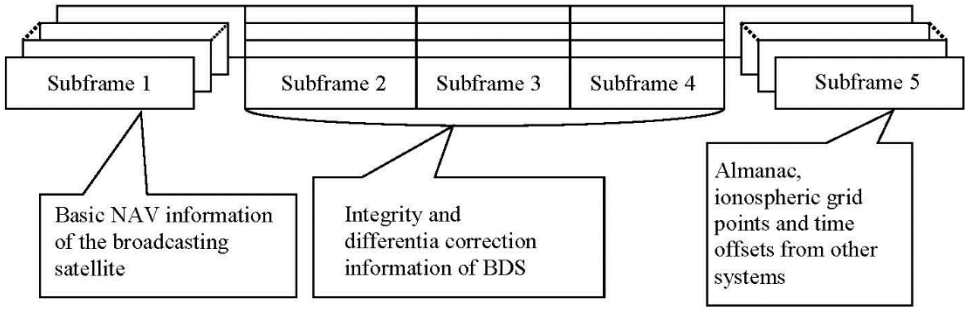

Fig 2. Frame structure and information contents of NAV message in format D2

Information about ionospheric grid is included in 2 Tables. It contains China area from 70 deg to 145 deg east longitude and from 7.5 deg to 55 deg north latitude. Table grid 2 is delayed 2.5 deg latitude in term of Table grid 1 (Fig. 3). Message D2 NAV contains values for grid 1 in pages 1–13, and for grid 2 in pages 60–73. Values in Table 2 are numbered from 1 to 160, in Table 3 are numbered from 161 to 320.

Tab. 2. Ionospheric data in Table 1

B\L	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145
55	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160
50	9	19	29	39	49	59	69	79	89	99	109	119	129	139	149	159
45	8	18	28	38	48	58	68	78	88	98	108	118	128	138	148	158
40	7	17	27	37	47	57	67	77	87	97	107	117	127	137	147	157
35	6	16	26	36	46	56	66	76	86	96	106	116	126	136	146	156
30	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155
25	4	14	24	34	44	54	64	74	84	94	104	114	124	134	144	154
20	3	13	23	33	43	53	63	73	83	93	103	113	123	133	143	153
15	2	12	22	32	42	52	62	72	82	92	102	112	122	132	142	152
10	1	11	21	31	41	51	61	71	81	91	101	111	121	131	141	151

Tab. 3. Ionospheric data in Table 2

B\L	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145
52.5	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320
47.5	169	179	189	199	209	219	229	239	249	259	269	279	289	299	309	319
42.5	168	178	188	198	208	218	228	238	248	258	268	278	288	298	308	318
37.5	167	177	187	197	207	217	227	237	247	257	267	277	287	297	307	317
32.5	166	176	186	196	206	216	226	236	246	256	266	276	286	296	306	316
27.5	165	175	185	195	205	215	225	235	245	255	265	275	285	295	305	315
22.5	164	174	184	194	204	214	224	234	244	254	264	274	284	294	304	314
17.5	163	173	183	193	203	213	223	233	243	253	263	273	283	293	303	313
12.5	162	172	182	192	202	212	222	232	242	252	262	272	282	292	302	312
7.5	161	171	181	191	201	211	221	231	241	251	261	271	281	291	301	311

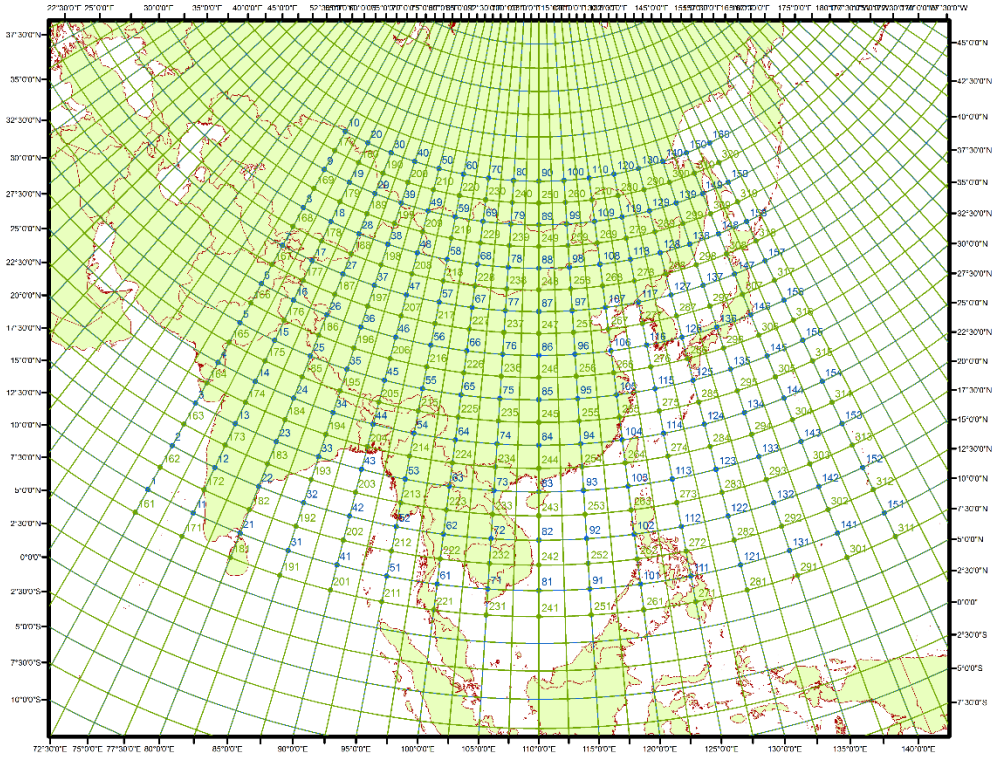

Fig. 3. Ionospheric grid 1 i 2

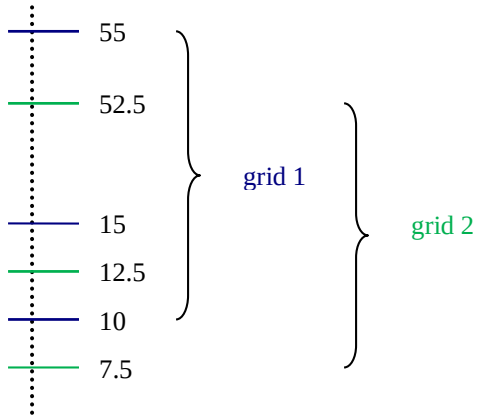

Fig. 4. Table grid 2 delayed 2.5° latitude in term of Table grid 1

Probably ionospheric data placed in two Tables in conjunction with D2 NAV message organization and capacity; 2.5 deg displacement in Tables gives two more times data about delays about ionospheric impact, which can be used for calculation more accurate measurement points data interpolation. In that effect the smallest data interpolation area is 2.5 deg latitude and 5 deg longitude square.

Grid calculation by geographical coordinates indicates convergence of meridians. Interpolation area (on the 375 km high) has field square:

- in the smallest (7.5 deg) latitude: (ΔB = 2.5 deg) ≈ 394 km; (ΔL = 5deg) ≈ ≈ 381 km;
- in the biggest (55 deg) latitude: (ΔB = 2.5 deg) ≈ 394 km; (ΔL = 5deg) ≈ ≈ 452 km.

Application bilinear interpolation can give not satisfied results if ionospheric model resolution is deeply better than mentioned grid joints above.

IONOSPHERIC TABLE DATA IDENTIFICATION

In case of IGP (Ionospheric Grid Points) knowledge ICD BDS has given formulas for grid joint defying. If IGP ≤ 160 than each data from Table point has:

$$B = 5° + (IGP - INT((IGP - 1)/10) \times 10) \times 5°; \quad (1)$$

$$L = 70° + INT((IGP - 1)/10) \times 5°. \quad (2)$$

If IGP > 160, than each data from Table points has:

$$B = 2.5° + (IGP - 160 - INT((IGP - 161)/10) \times 10) \times 5°; \quad (3)$$

$$L = 70° + INT((IGP - 161)/10) \times 5°. \quad (4)$$

Formula analysis can affirm that grid data number IGP determines left grid joint coordinates. Authors did not determined formulas for IGP number determination in case of place of observation – geographical coordinates. They are as follows:

– for grid 1(Y)

$$IGP^{Y} = INT((L - 70)/5) \times 10° + INT((B - 10)/5) + 1; \quad (5)$$

– for grid 2(Z)

$$IGP^{Z} = INT((L - 70)/5) \times 10° + INT((B - 7.5)/5) + 161. \quad (6)$$

DATA DETERMINATION FOR 4 POINT OF INTERPOLATION

If we have IGP numbers of both grids, we have to estimate all corners of square, where interpolation will began. We have 3 possibilities of points localization (grid number — superscript; IGP number — subscript):

P1 — if $B_{IGP}{}^{Y}{}_{+1} > B_{P1} > B_{IGP}{}^{Y} + 2.5°$
$L_{IGP}{}^{Y}{}_{+11} > L_{P1} > L_{IGP}{}^{Y}{}_{+11}$,

P2 — if $B_{IGP}{}^{Z}{}_{+1} > B_{P2} > B_{IGP}{}^{Z} + 2.5°$
$L_{IGP}{}^{Y}{}_{+11} > L_{P2} > L_{IGP}{}^{Y}{}_{+11}$,

P3 — if $B_{IGP}{}^{Z} + 2.5° > B_{P3} > B_{IGP}{}^{Z}$
$L_{IGP}{}^{Z}{}_{+11} > L_{P3} > L_{IGP}{}^{Z}{}_{+11}$.

This situation you can see in Figure 5.

(1) Points for interpolation:

$$IGP_1{}^{Z} = IGP^{Z+1},$$

$$IGP_2{}^{Z} = IGP^{Z+11},$$

$$IGP_3{}^{Y} = IGP^{Y+12},$$

$$IGP_4{}^{Y} = IGP^{Y+1},$$

where superscript means grid number and subscript means IGP number.

For better grids viewing indicated Y letter for grid 1 (blue) and Z letter for grid 2 (green). Similarly its possible to find interpolation points for coordination of points 2 and 3:

Point No. 2	Point No. 3
$IGP_1 = IGP^Y$,	$IGP_1 = IGP^Z$,
$IGP_2 = IGP^{Y+10}$,	$IGP_2 = IGP^{Z+10}$,
$IGP_3 = IGP^{Z+11}$,	$IGP_3 = IGP^{Y+10}$.

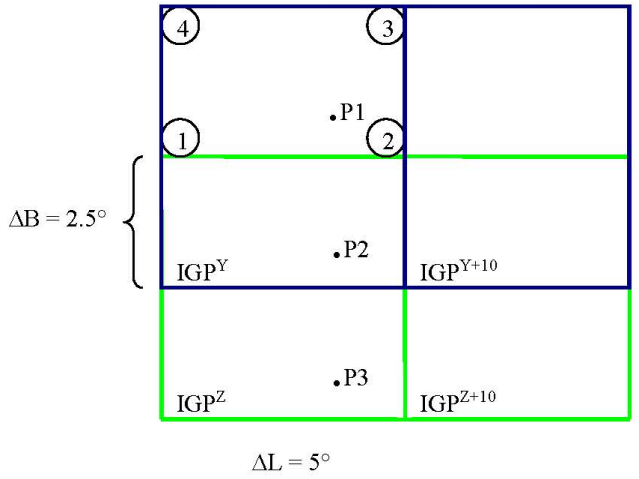

Fig. 5. Grids 1 and 2 displaced in latitude for 2.5 deg with possibility of points localization

BILINEAR INTERPOLATION ALGORITHM IN 4 POINTS GRID

After automatic coordinates assignment and values for 4 points from IGP Table, where between them interpolates $d\tau$ and GIVEI values for each one, we can calculate bilinear interpolation. Formulas from ICS BDS are as follows:

$$d\tau = \frac{\sum_{i=1}^{4} \omega_i VTEC_i}{\sum_{i=1}^{4} \omega_i}, \tag{7}$$

where:

$$\left.\begin{aligned} \omega_1 &= (1 - X_P)(1 - Y_P), \\ \omega_2 &= X_P(1 - Y_P), \\ \omega_3 &= X_P Y_P, \\ \omega_4 &= (1 - X_P)Y_P, \end{aligned}\right\} \tag{8}$$

with:

$$\left.\begin{aligned} X_P &= \frac{L_P - L_1}{L_2 - L_1}, \\ Y_P &= \frac{B_P - B_1}{B_4 - B_1}. \end{aligned}\right. \tag{9}$$

Formulas analysis (7–9) determines the denominator which equals 1, sum of all factors (coefficients) equals 1. It means that interpolated value has weighted from point distance from all corners of square.

IONOSPHERIC GRID PROPOSITION

It is suggested grid No. 1 (Y — blue), like in D2 NAV message, and grid No. 3(X — red) displaced in latitude and longitude for 2.5 deg regard to grid 1. Grid determination by geographical coordinates prescripts taking into account the convergence of meridians. Interpolation area is a square with dimensions:
– in the smallest (7.5 deg) latitude: (ΔB = 2.5 deg) ≈ 394 km; (Δ (L = 2.5 deg) ≈ 390 km;
– in the biggest (55 deg) latitude: (ΔB = 2.5 deg) ≈ 394 km; ((ΔL = 2.5 deg) ≈ 226 km.

Tab. 4. Ionospheric data in proposition Table 2

B\L	72.5	77.5	82.5	87.5	92.5	97.5	102.5	107.5	112.5	etc.	147.5
52.5	170	180	190	200	210	220	230	240	250	to	320
47.5	169	179	189	199	209	219	229	239	249		319
42.5	168	178	188	198	208	218	228	238	248		318
37.5	167	177	187	197	207	217	227	237	247		317
32.5	166	176	186	196	206	216	226	236	246		316
27.5	165	175	185	195	205	215	225	235	245		315
22.5	164	174	184	194	204	214	224	234	244		314
17.5	163	173	183	193	203	213	223	233	243		313
12.5	162	172	182	192	202	212	222	232	242		312
7.5	161	171	181	191	201	211	221	231	241		311

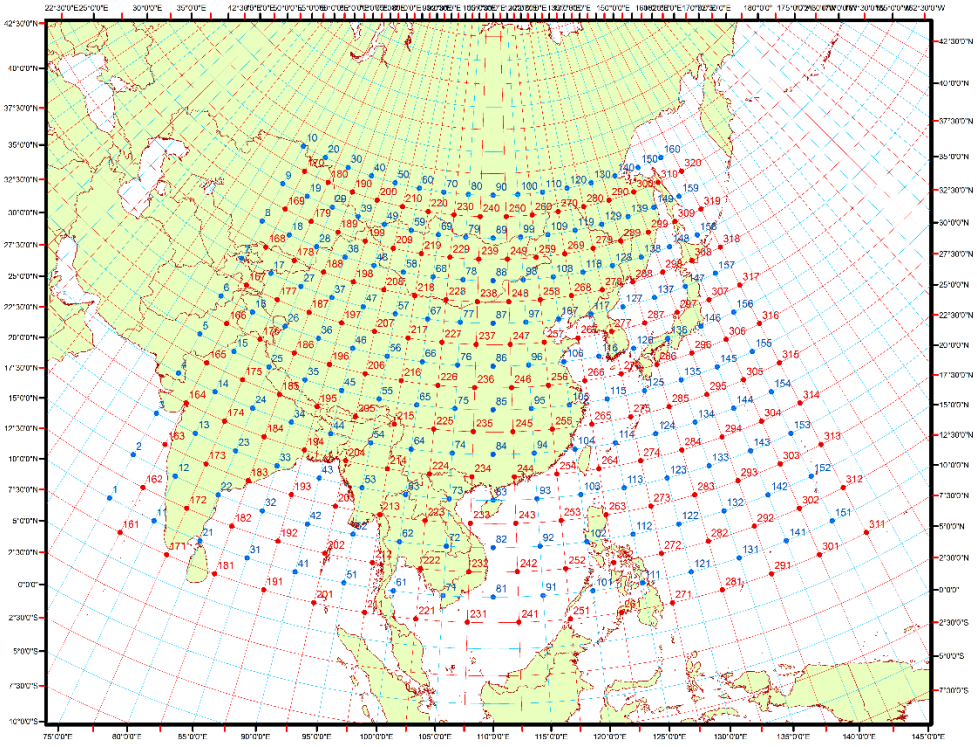

Fig. 6. Grid 1 and 3 dislocated in 2.5 deg of latitude and longitude

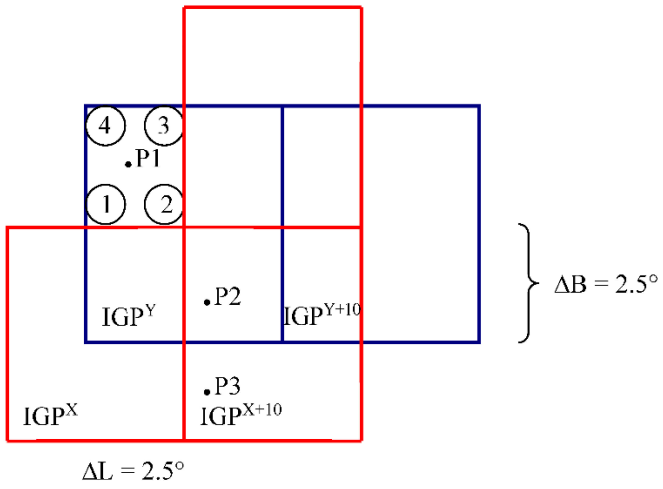

Fig. 7. Grid 1 and 3 dislocated in 2.5 deg of latitude and longitude with possibility of points localization

In case of grid No. 3 (X) determination formulas of grid joint coordinates are as follows:

$$B = 2.5° + (IGP - 160 - (INT((IGP - 161)/10)) \times 10) \times 5°; \quad (10)$$

$$L = 72.5° + INT((IGP - 161)/10) \times 5°. \quad (11)$$

- Localization observing points identification

Case 1	Case 2	Case 3
$(B_{IGPY+1} + 2.5°) > \mathbf{B_{P1}} > B_{IGPY+1}$	$(B_{IGPX+1} + 2.5°) > \mathbf{B_{P2}} > B_{IGPX}$	$(B_{IGPY} + 2.5°) > \mathbf{B_{P3}} > B_{IGPY}$
$(L_{IGPY} + 2.5°) > \mathbf{L_{P1}} > L_{IGPY}$	$(L_{IGPY} + 2.5°) > \mathbf{L_{P2}} > L_{IGPY}$	$(L_{IGPY} + 2.5°) > \mathbf{L_{P3}} > L_{IGPY}$

If we have point localization from grids 1(Y) and 3(X), it is possible to determine coordination points needed for interpolation. Interpolation happens a little bit different than grid nr 1 and 2 usage. In first way it interpolates delay values in grid No. 1 and 3 line points.

Points for interpolation:
Case 1

$$IGP_1 = IGP_Y,$$

$$IGP_2 = \text{interpolation between } IGP_Y, IGP_{X+10}, IGP_{Y+10}, IGP_{X+11}, \quad (12)$$

$$IGP_3 = IGP_{X+11},$$

$$IGP_4 = \text{interpolation between } IGP_Y, IGP_{X+11}, IGP_{Y+1}, IGP_{X+1}. \quad (13)$$

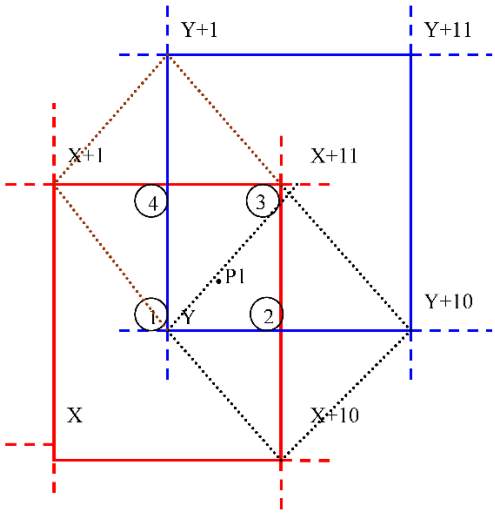

Fig. 8. Data interpolation in grids 1 and 3 (the dotted line marks the interpolation area crossed grids 2 and 4)

It finds the rest of points in analogical way.

EXAMPLE OF CALCULATION IONOSPHERIC GRIDS USAGE IN BDS

In calculation used artificial data, not bound (correlated) with state of ionosphere. Grids were delayed only in latitude, as it proposed in BDS.

Calculation points — near Beijing:

P_1 (B = 44°, L = 117°), P_2 (B = 41°, L = 118°), P_3 (B = 39°, L = 118°).

Identification data from ionospheric Tables.

Point 1

- IGP data identification
  - in grid 1(Y)

    $IGP^1 = INT((117 - 70)/5) \times 10 + INT((44 - 10)/5) + 1 = 90+7 = 97;$
  - in grid 2(Z)

  $IGP^2 = INT((117 - 70)/5) \times 10 + INT((44 - 7.5)/5) + 161 = 90 + 168 = 258.$
- Grid joint coordinate determination:
  - in grid 1(Y)

$$L^Y_1 = 70° + INT((97 - 1)/10) \times 5 = 115°,$$

$B^Y_1 = 5° + ((97 - INT((97 - 1)/10) \times 10) \times 5° = 5° + ((97 - 90) \times 10) \times 5° = 5° + 35° = 40°;$

  - in grid 2(Z)

$$L^Z_1 = 70° + INT((258 - 161)/10) \times 5° = 70° + 45° = 115°,$$

$B^Z_1 = 2.5° + (258 - 160 - INT((258 - 161)/10 \times 10) \times 5° = 2.5° + (98 - 90) \times 5° = 42.5°.$

- Four points coordinate determination for interpolation. Grid points, from which there are interpolation values $d\tau$, are the points with coordinates and delay data Table $d\tau$:

$1 = IGP^Z$ (B = 42.5°, L = 115°, 35),

$2 = IGP^{Z+10}$ (B = 42.5, L = 120°, 60),

$3 = IGP^{Y+11}$ (B = 45°, L = 120°, 60),

$4 = IGP^{Y+1}$ (B = 45°, L = 115°, 40).

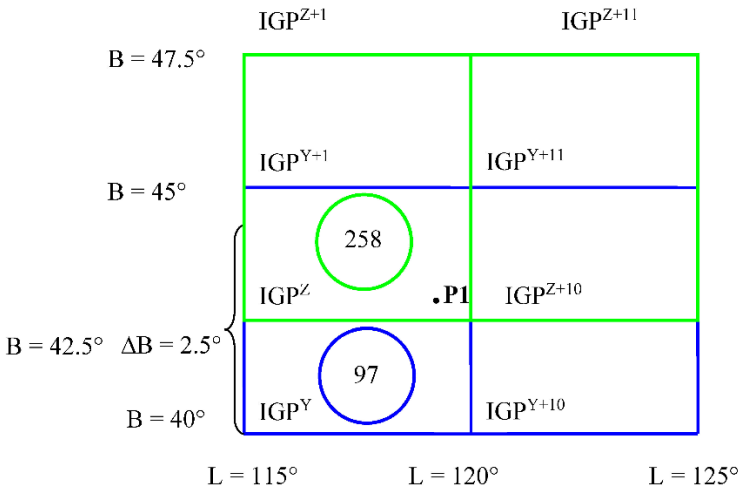

Fig. 9. Grid 1 and 2 dislocated in 2.5 deg of latitude with possibility of point P1 localization

- Bilinear interpolation calculation (7–9):

$$X^P = \frac{L_{P1} - L_1}{L_2 - L_1}, \text{ or } X^P = \frac{117 - 115}{120 - 115} = 0{,}67,$$

$$Y^P = \frac{B_{P1} - B_1}{B_4 - B}, \text{ or } Y^P = \frac{44 - 42{,}5}{45 - 42{,}5} = 0{,}2;$$

$$\omega_1 = (1 - X_P)(1 - Y_P) = 0.27,$$

$$\omega_2 = X_P(1 - Y_P) = 0.53,$$

$$\omega_3 = X_P Y_P = 0.13,$$

$$\omega_4 = (1 - X_P)Y_P = 0.07.$$

So we have $d\tau_{P1} = 51.85$.

EXAMPLE OF CALCULATION SUGGESTED IONOSPHERIC GRIDS USAGE IN BDS

In calculation were used the same points as in previous example.

- IGP data identification:

– in grid 1(Y) and grid 3 (X):

$$IGP^{Y}_{1} = INT((117 - 70)/5) \times 10 + INT((44 - 10)/5) + 1 = \mathbf{97},$$

$$IGP^{X}_{1} = INT((117 - 72.5)/5) \times 10 + INT((44 - 7.5)/5) + 161 = \mathbf{248}.$$

- Grid joint coordinate determination:
  – in grid 1(Y)

$$B^{Y} = 5° + (IGP - INT(IGP - 1)/10) \times 5° = 40°,$$

$$L^{Y} = 70° + INT((97 - 1)/10) \times 5° = 115°;$$

  – in grid 3(X)

$$B^{X} = 2.5° + (IGP - 160 - (INT((IGP - 161)/10) \times 10)) \times 5° =$$
$$= 2.5° + (248 - 160 - (INT((248 - 161)/10) \times 10)) \times 5° = 42.5°,$$

$$L^{X} = 72.5° + INT((IGP\text{-}161)/10) \times 5° = 112{,}5.$$

- Estimation the position of points related to grid 1(Z) i 3(X):

$$\text{if } (B_{IGP(X)} + 2.5°) > B_{P1} > B_{IGP(X)} \qquad 45° > 44° > 42.5°,$$

$$L_{IGP(X+10)} > L_{P1} > L_{IGP(Y)} \qquad 117{,}5° > 117° > 115°.$$

Position of the point is equal to one showed at Figure 8. Points for interpolation are 1, 2, 3, 4. Points 1 and 3 should also interpolate. Interpolation points from crossed grids 1 and 3 are a mean value from points lying down near interpolated point.

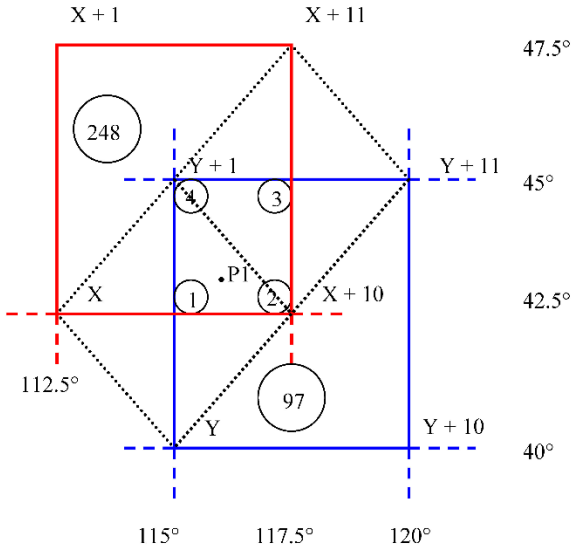

Fig. 10. Ionospheric grid 1(Y) and 3(X) points for interpolation

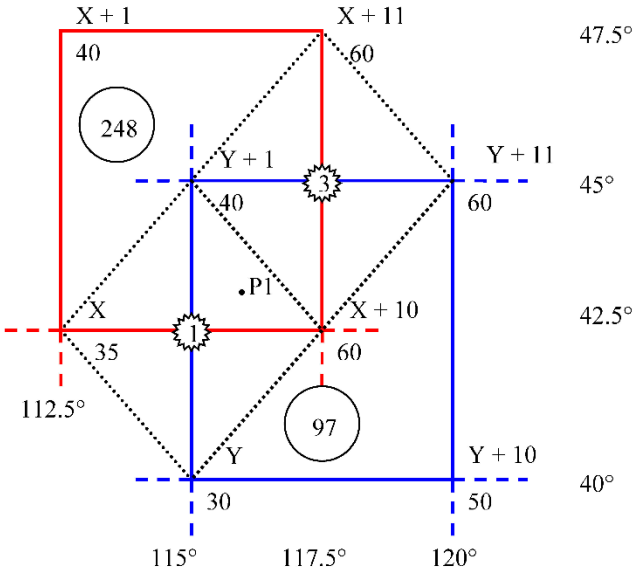

Fig. 11. Delays data used in interpolation

Results of calculation:

$d\tau_1 = (35 + 30 + 60 + 40)/4 = 41.25$ $\quad X_P = 0.8$ $\quad \omega_1 = 0.08$

$d\tau_2 = 60$ $\quad Y_P = 0,6$ $\quad \omega_2 = 0.32$

$d\tau_3 = (40 + 60 + 60 + 60)/4 = 55$ $\quad \omega_3 = 0.48$

$d\tau_4 = 60$ $\quad \underline{\omega_4 = 0.12}$

$\sum \omega = 1.00$

The final result of interpolation is $\boldsymbol{d\tau_{P1}} = 56.1$. The delay was 51.85 in interpolation from grids 1 and 2. Difference is undoubtedly due to more precisely ionospheric state data of interpolated point.

SUMMARY

Usage of two interpolation grids delayed in longitude and latitude, gives possibility to more accurate interpolation values of $\boldsymbol{d\tau}$ delays from BDS messages; 2.5 deg in longitude and latitude delays gives two more data about ionospheric

influence, used for more accurate measurement point interpolation. In that effect the smallest area, in which data are interpolated, is square with dimensions: 2.5 deg latitude and 2.5 deg longitude.

Precision of interpolation depends in big case from accuracy and resolution of ionospheric state model. If resolution of ionospheric model is deeply better than joint grids distance, than bilinear interpolation usage can't give satisfactory results.

Restriction ionospheric grids for China area gives ionospheric model limitations in usage for lower height satellites, especially that one on the close of ionospheric area.

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[1] *BeiDou Navigation Satellite System, Signal In Space, Interface Control Document*, Open Service Signal (Version 2.0), China Satellite Navigation Office, December 2013, [online], http://www2.unb.ca/gge/Resources/beidou_icd_english_ver2.0.pdf [access 17.06.2016].

Received September 2016
Reviewed March 2017
Published 23.10.2017

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STRESZCZENIE

W artykule opisano sposób wykorzystania danych jonosferycznych zawartych w dwóch tabelach przesyłanych w depeszy D2 NAV chińskiego systemu BeiDou. Określono szczegółowe wzory umożliwiające określenie danych zawartych w tabelach. Zaproponowano modyfikację tabeli danych nr 2 oraz określono wzory pozwalające na korzystanie z tej tabeli. Podano przykłady liczbowe określenia danych w systemie tabel BeiDou oraz w systemie zaproponowanym.