MODELING THE IONOSPHERE WITH PRARE

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ABSTRACT

The two-way microwave satellite tracking system PRARE is operating onboard ERS-2 since May 1995, the routine product generation started January 1st, 1996. Besides very precise 2-way range and range-rate measurements between the space segment and a globally distributed network of tracking stations which are used for orbit determination, point positioning, Earth rotation and gravity field parameter estimation, two different methods are used to derive the corresponding ionospheric corrections as well as the total electron content (TEC) in slant and vertical direction:

a.) The one-way code travel time difference between the simultaneously transmitted X- and S-band signals, which is measured in the ground stations continuously during every pass.

b.) The continuously available one per second two-way range and range-rate measurements, which are based on different propagation velocities (group resp. phase velocity). This can be used to calculate the ionospheric correction using the DRVID (differenced range versus integrated doppler) principle.

The paper describes both methods as well as first results to calibrate and validate the ionospheric data. Absolute calibration biases have been derived for stations operated in common view mode or by comparison with the regional ionospheric model NTCM2. Finally, the PRARE derived TEC data are compared with the international reference ionosphere IRI95, daily global ionospheric maps derived from GPS carrier phase data and TOPEX dual-frequency altimeter derived TEC data. Further plans to calibrate and validate the data are discussed.

1. THE PRARE TRACKING SYSTEM

The PRARE system is a space-borne, two-way, two-frequency microwave satellite tracking system with onboard data storage and central data preprocessing, allowing data analysis within a very short time delay. PRARE has been tested onboard the Russian Meteorological Satellite METEOR-3/7 between January 1994 and October 1995 and is now operated in redundant configuration on ERS-2. The system consists of a space, a ground and a control segment.

The ground segment comprises 29 transportable, autonomously operating and globally distributed ground stations owned and operated by 13 different international user groups. The present network consists of 17 globally distributed stations (cf. figure 4) which acquire due to the weather independency about 600 passes per week. During every pass the ground stations transmit all information to the space segment (e.g. the observed X-band vs. S-band travel time differences) which are necessary for the later correction of the signals. As long as no obstructions block the line of sight to the satellite, the ground stations are tracking nearly from horizon. Polar stations like Ny Alesund contribute with 14 passes/day (due to ERS-2 inclination). It is planned to extend the network to about 25 stations until mid of 1997.

The control segment is established in Germany and is composed by a Master Station in Oberpfaffenhofen (network management and support, data preprocessing, quality control and distribution), a Monitoring and System Command Station in Stuttgart (space segment control, data dumping) and a Calibration Station in Potsdam (periodic calibration of PRARE versus Laser).

The space segment measures the two-way range and the two-way Doppler-shifted signal very precisely. The overall noise of the pre-processed full rate range data is about 2.5 - 6.5 cm (depending on the geographic location of the ground station and corresponding ERS-2 solar-pannel multipath effects) and for the doppler data 0.1 mm/s (30 seconds integration interval). The compressed normal point noise is less than 1 cm resp. 0.015 mm/s [Bedrich et al., 1997] .

2. TEC DETERMINATION FUNDAMENTALS

The effect of the ionosphere on the propagation time delta tau [sec] of a radio signal is [Hartl, 1980] :

$$[1] \quad \delta\tau = \pm \frac{40.3}{c f^2} \int_{S_1}^{S_2} N_e \, ds = \pm \frac{40.3}{c f^2} \, TEC$$

where f is the frequency [Hz] of the radio signal, c the velocity of light [m/s] and Ne the electron density [electrons/m^3]. The sign of the correction is positive in case of range signals (group velocity < c) resp. negative in case of doppler measurements (phase velocity > c). The integral is also referred as the total electron content TEC [electrons/m^2] along the transmission path, 10^{16} electrons/m^2 are defined as 1 TEC-unit (TECU).

If a second frequency is used (e.g. PRARE, TOPEX altimeter), TEC can easily be determined due to the dispersive behaviour of the ionosphere:

$$[2] \quad TEC = \frac{c}{40.3} \left[\frac{1}{f_1^2} - \frac{1}{f_2^2} \right]^{1} \delta\tau_{f_1 f_2}$$

where delta tau (f1f2) is the travel time difference between both radio signals.

To scale the observed TEC from slant (PRARE ground station - satellite) to the vertical direction (TEC90), a simple mapping function (1/cos(z)) has been used, where z is the angle between slant and vertical direction. For the PRARE data investigation we applied a single layer model assuming that all free electrons are concentrated in a shell of infinitesimal thickness. The height of this idealized layer h_{ion} is usually set to the height of the expected maximum electron density N*e*, which is expected to be a function of the geocentric latitude and the sun-fixed longitude. In the present analysis h_{ion}, is set to constant 400 km, although h_{ion} can vary by several 10 km depending on e.g. day/night variations, geographical location or solar activity. The PRARE TEC90 are therefore referred to the vertical direction at the intersection point of the slant PRARE observation and the single layer (rf. figure 2). Table 1 shows the ionospheric correction error in case of 1 TECU uncertainty for different sensor frequencies f_1 (rf. [1]).

Station	PRARE/ERS-2	Altimeter/ERS-2	Altimeter/TOPEX
f_1 [GHz]	8.489	13.8	13.6
f_2 [GHz]	2.248	-	5.3
k [mm]	5.6	2.1	2.2

Table 1: Ionospheric correction error k [mm] in case of 1 TECU uncertainty

3. PRARE IONOSPHERIC MEASUREMENTS

The PRARE system offers two different approaches to derive ionospheric measurements tau_{f1f2} (rf. [2]):

Every second the PRARE ground stations observe the one-way travel time difference between the demodulated 10 MHz PN-code of the X-band and the 1 MHz PN-code of the S-band, both transmitted quasi-simultaneously from the PRARE space segment, duringa satellite pass. These one per second observations are averaged during a four second interval and retransmitted to the space segment within the low rate data stream, where they are stored in the onboard memory to be used for later ionospheric correction of the range and doppler tracking data. The noise of the ionospheric code data is about 1 ns resp. 4 TECU due to S-band signal noise.

Alternatively the one per second two-way range and doppler data can be used to determine the ionospheric characteristics, because the propagation speed of the range signal is the group velocity, whereas the doppler signals propagate with phase velocity. This corresponds to inverse signs for the corresponding ionospheric corrections (rf. chapter 2). Because all other corrections have to be applied for both data types with the same sign, the difference between two adjoining range data and the corresponding doppler (range-rate) data gives the double influence of the ionosphere. This principle is called "Differenced Range versus Integrated Doppler (DRVID)". To derive the unknown bias of the DRVID

data, the code data can be used. The noise of the one per second DRVID data is governed by the noise of the range signal which is about 2.5 to 6.5 cm (corresponding to 0.8 to 2.2 ns for tau_{f1f2} resp. 3.3 to 8.8 TECU) depending on the latitude of the ground station resp. corresponding ERS-2 solar panel multipath effects. The DRVID principle is therefore also suitable for multipath detection. Smoothing of the DRVID data (e.g. polynomial fitting) can simply reduce the noise to about 0.5 to 1.0 ns resp. 2 to 4 TECU.

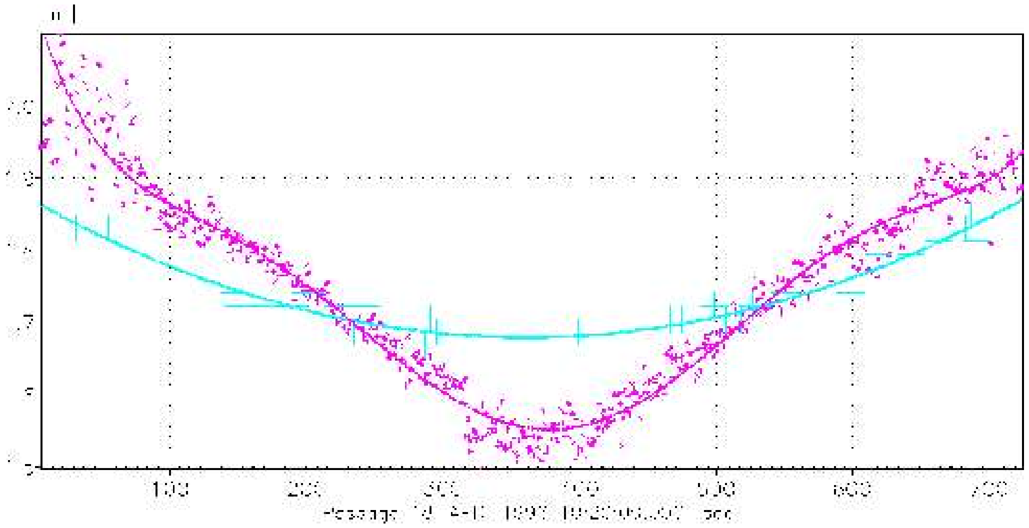

Figure 1: 2-way ionospheric DRVID (*) and Code (+) X-band correction for Oberpfaffenhofen on April 18, 1996 10:20:09 UTC

Due to the specific design of the PRARE system, the ionospheric information from the global network is available at the Master Station within a few hours delay, which is a great advantage with respect to e.g. GPS.

4. BIAS DETERMINATION

To use these PRARE derived observations for ionospheric modeling or tracking data correction, thedata have to be calibrated and validated. First, the bias at the space segment due to the fact that there might be an internal delay between the X- and S-band signal transmission has to be determined. Additionally, the relative biases of the code travel time differences between all PRARE ground stations have to be known. Because transmitter and receiver biases can't be solved independently, only a ground station dependent bias can be solved (including the transmitter bias). Three different approaches have been used so far, which are shortly described in the following.

4.1 Common View Technique

If common view observations of two ground stations are available the biases can be derived in a least square solution assuming that the derived vertical TEC90 of both stations at the same sub-ionospheric latitude should be the same and that longitudinal differences can be disregarded (rf. figure 2).

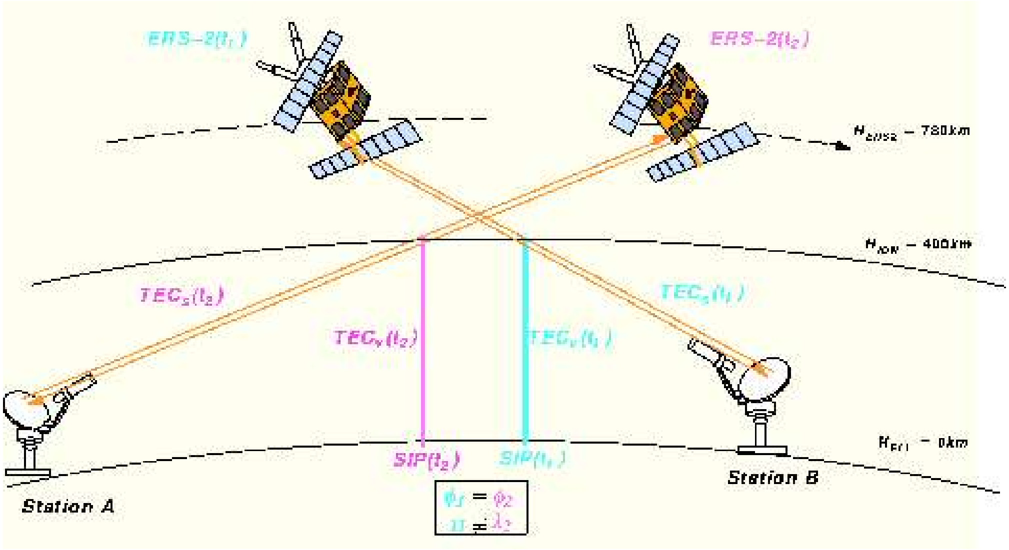

Figure 2: Principle of Common View Technique to derive PRARE DRVID biases

Due to the relatively low altitude of ERS-2, this approach could be performed only for 12 ground stations. The typical sigma of the solved biases is about 1 to 2 ns (resp. 4 to 8 TECU) depending on the common view geometry (total resp. longitudinal distance between the stations), the number of used passes, the measurement accuracy of the DRVID data (0.5 to 1.0 ns) and the mapping function to scale the slant into vertical TEC (0.5 ns) . Figure 3 shows an example for station #08 (Matera) which has been compared with station #21 (Potsdam) in 92 passes during weeks 29/96 until 45/96. The solved bias was 34.6 ns with a sigma of 1.3 ns.

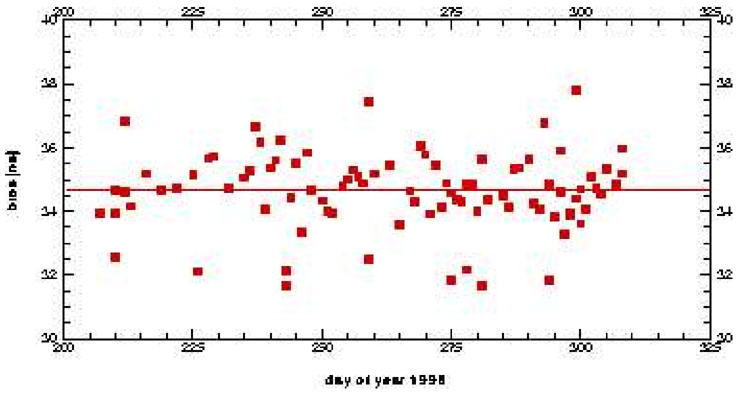

Figure 3: Bias of station #08 during weeks 29/96 until 45/96

4.2 Constant Night-Time Ionosphere

Another approach is to solve for the bias during night time passes only, when the ionosphere is nearly constant. Having a sufficient number of passes, a mean bias can be derived for each station with a typical sigma of about 1.5 ns [6 TECU]. The resulting mean bias values have been compared with those derived with the common view technique. All differences were found to be smaller than 0.5 ns (rf. table 2).

4.3 Regional NTCM2 Model

PRARE DRVID data of thre stations and two time periods (July, September 96) have been compared by Jakowski (DLR Neustrelitz) with the regional Neustrelitz Total Electron Content Model NTCM2 [Jakowski, 1994] .This model consists of 60 coefficients which describe the semi-diurnal and diurnal, semi-annual and annual, solar zenith angle resp. solar cycle dependency of the ionosphere in Europe. The coefficients of NTCM2 are based on GPS carrier phase data. Because the rms difference between the GPS data and NTCM2 is about 0.8 TECU, this model should be suitable for PRARE DRVID calibration. A disadvantage for the comparison of PRARE data with NTCM2 is the fact that the plasmaspheric part of the ionosphere is included in the model. Therefore a constant value of 2 TECU has been assumed for all comparisons, daily fluctuations have been neglected. As can be seen from table 2 the biases derived with NTCM2 are for all three stations 1.0 to 1.4 ns (4 to 6 TECU) larger than the biases derived with the Common View Technique resp. assuming a constant night-time ionosphere. This might be due to the fact that PRARE TEC90 values are valid for the ionosphere up to 780 km and that no assumption was made for the part of the ionosphere between 780 km and the plasmasphere. The differences will be further investigated using data from other stations and time periods.

Station	Common View	Constant Ionosphere	NTCM2 Model
#02	19.2 +- 1.6	19.4 +- 1.7	20.6 +- 1.2
#03	29.7 +- 1.2	29.8+-1.6	30.7 +- 1.1
#21	27.7 +- 1.1	27.7+-1.2	28.9 +- 1.1

Table 2: PRARE DRVID bias and sigma [ns] for station #02, #03 and #21 derived with different methods

5. COMPARISON WITH IRI95 AND CODE GIM

PRARE DRVID derived TEC90 data have been compared with the International Reference Ionosphere 95 (IRI95) [Biliza, 1996] [Bilitza, 1996] and with daily Global Ionosphere Maps (GIM) based on GPS carrier phase data routinely produced by the CODE analysis center [Schaer et al., 1996] .

The time period chosen for this comparison was week 02/97 until week 06/97 (35 days resp. one ERS-2 cycle), when the PRARE data distribution was excellent. All available PRARE DRVID data (no elevation cut-off, no data edit criteria) have been used to get a complete overview about the PRARE data quality. Biases have been applied as derived from common view resp. constant ionosphere.

Figure 4 shows the global differences for the GIM comparison, table 3 the minimum, maximum, mean and rms differences [TECU] for both comparisons. It should be mentioned that CODE GIM agree very good if compared with IRI95 for the investigated time period (mean=0.6 TECU, RMS=3.2 TECU).

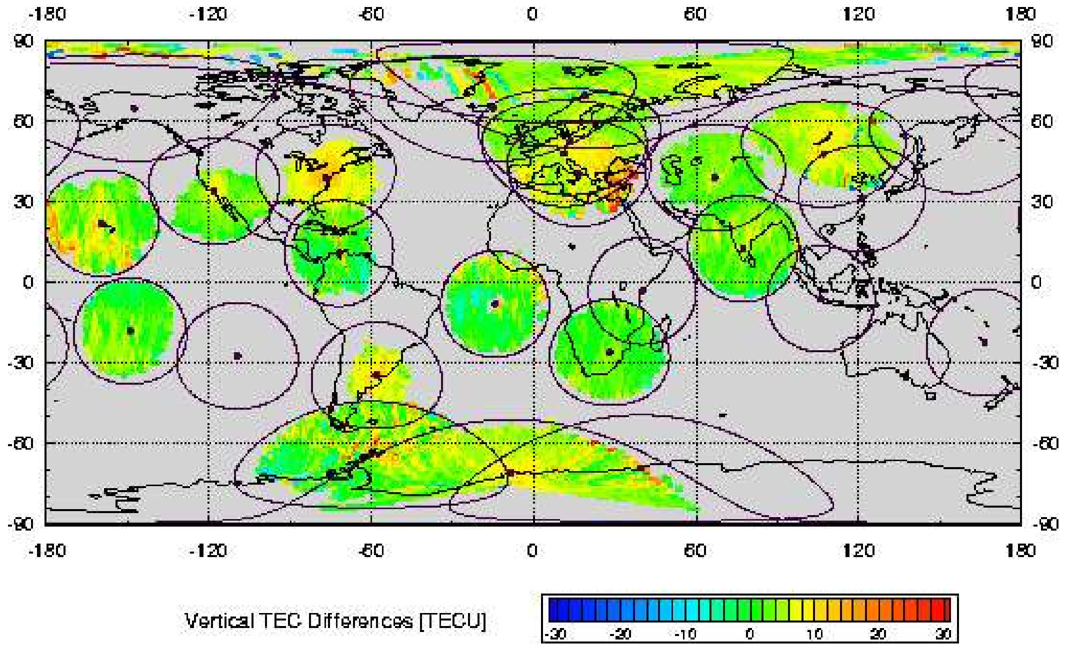

Figure 4: TEC90 differences between PRARE DRVID and CODE GIM

week	obs	min	max	mean	rms
02/97	239798	-24.7	36.0	3.3	6.4
03/97	231303	-25.2	36.2	3.1	6.2
04/97	239145	-33.6	40.5	3.6	6.9
05/97	254586	-24.2	34.8	2.6	5.8
06/97	238305	-20.4	36.7	3.2	6.6
total	1203137	-25.6	36.9	3.2	6.4

Table 3a: Minimum, maximum, mean and rms differences [TECU] between PRARE DRVID and IRI95

week	#obs	min	max	mean	rms
02/97	239798	-24.3	36.7	3.1	6.1
03/97	231303	-25.0	35.4	3.1	5.9
04/97	239145	-34.1	41.3	3.4	6.8
05/97	254586	-24.1	36.9	2.7	5.7
06/97	238305	-20.0	37.5	2.6	6.2
total	1203137	-25.5	37.6	3.0	6.1

Table 3b: Minimum, maximum, mean and rms differences [TECU] between PRARE DRVID and CODE GIM

The PRARE TEC90 data have a mean offset against IRI95 of 3.2 TECU resp. 3.0 TECU against CODE GIM, which corresponds e.g. to 6.5 mm for the ERS-2 altimeter ionospheric correction. Both analysis have also been performed for day resp. nigth passes only. No major discrepancies have been found. The remaining offset may be due to the fact that no PRARE data were edited for this comparison and/or to up to now insufficient PRARE bias determination.

6. COMPARISON WITH TOPEX DUAL-FREQUENCY ALTIMETER DATA

The TOPEX dual-frequency altimeter (13.6 GHz, 5.3 GHz) provides independant global TEC90 measurements with an residual accuracy less than 3 TECU [Yuan et al., 1996]. Although the orbital parameters of ERS-2 and TOPEX are different (a=7167 resp. 7703 km, i=98.5 resp. 66 degrees), it is possible to compare TEC90 data from both missions if the corresponding time tags differ by e.g. less than 1 hour. The corresponding TEC90 differences have been averaged to 5x5 degree mean values. Figure 5 shows the TEC90 differences for the period March 25 until April 23, 1996.

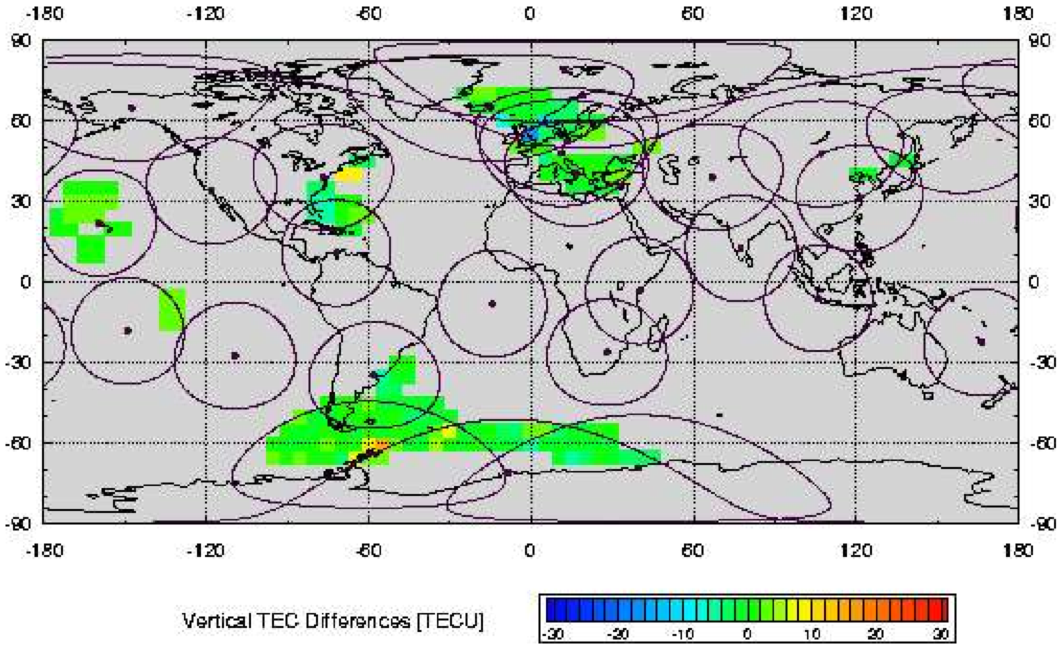

Figure 5: PRARE/TOPEX TEC90 differences for period March 25 until April 23, 1996.

As can be seen, the differences between PRARE DRVID and TOPEX altimeter data are below 4 TECU which is within the measurement accuracy of both systems. On the other hand, there should be a small bias between both systems (rf. chapter 4.3) because PRARE is - in contrary to TOPEX - not observing the complete ionosphere! It is assumed that this question will be solved if the 3 TECU offset of PRARE versus IRI 95 and CODE GIM will be eliminated e.g. by better bias determination.

7. FURTHER PLANS

The following investigations are planned to be performed in the very next time:

-Analyse of PRARE METEOR-3 DRVID data (no multipath available) to get additional biases

-Analyse bias offsets of NTCM2

-Fix station dependent biases

-Include edit criteria for "corrupt/mismodeled" PRARE DRVID data

-Analyse "corrupt/mismodeled" PRARE DRVID data

-Repeat comparison with other ionospheric models (Bent, IRI-90, PIM), other Global Ionospheric Maps (e.g. JPL GIMs [Yuan et al., 1996]) or additional TOPEX data

-Repeat TOPEX and model comparison for other periods and fixed biases

-Scale TEC90 from sub-ionospheric to ERS-2 sub-satellite point

-Include PRARE TEC90 data in ERS-2 altimeter processing

-Generate and distribute PRARE ionospheric products on a daily basis

8. SUMMARY

The PRARE system offers about 600 globally distributed passes per week containing (beside very precise range and range-rate observations) vertical TEC data with anaccuracy of about 2 of 4 TECU. First ground station dependent biases have been obtained for all stations with three independent methods. Comparisons of PRARE derived TEC values with IRI95 resp. CODE GIM show an offset of about 3 TECU with an rms of about 6 TECU. The differences versus TOPEX dual-frequency altimeter derived TEC data are within the measurement accuray of both systems. After investigation of some open points, calibrated PRARE ionospheric data should be available on a daily basis mid of 1997.

9. REFERENCES

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