Consolidated Laser Ranging Prediction Format
Version 1.01

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Abstract

The International Laser Ranging Service (ILRS) Predictions Formats Study Group was created at the 12th International Workshop on Laser Ranging and tasked with creating a consolidated laser ranging prediction format that could accurately predict positions and ranges for a much wider variety of laser ranging targets than had been previously possible. While several complications arise in creating and implementing a format for such divergent targets, the opportunities for ranging exotic targets from ordinary ranging stations should compensate for any inconveniences.

Introduction

The satellite laser ranging (SLR) community of about 40 laser ranging stations has used the standard "Tuned IRV" prediction format for up to 20 years. This format consists of a satellite state vector (x, y, and z positions and velocities at a given time plus other parameters, one set per day per satellite) tuned to specific field integrator software and gravity field to provide maximum accuracy over the integration period. The format can be found at: ftp://cddis.gsfc.nasa.gov/pub/formats/tirv.format.

The ranging stations in the lunar laser ranging (LLR) community (2 stations routinely gathering data, at least 3 others lunar-capable, and several retired) have historically either developed their own prediction software or have ported others'. The software has used

one of about 3 lunar and planetary ephemeris packages, each containing a multi-year ephemeris.

Thus, the SLR community has generally used standard integrator software and gravity field models with predictions supplied on a weekly or (now) daily basis. The lunar community has used a standard multi-year ephemeris, a mix of interpolation software, and weekly earth orientation parameter predictions.

Lunar ranging has been restricted to a few stations due in large part to the low return signal strengths involved. The distance to the moon (R), combined with the $1/R^4$ scaling of the return signal strength to that transmitted, means only a few photo-electrons per minute are seen by current ranging systems using available technology.

This state of affairs has existed since the 1970s. There are now, however, the possibility of several new missions that could change everything. For instance, CRL would like to put a laser transponder on the moon. Groups at NASA are proposing transponders combined with altimeters for future planetary and asteroid missions. Transponders have a laser transmitter at both ends of the ranging link. The receive signal strength therefore is proportional to $1/R^2$ times the transmit energy. Because of this, the downlink energy is high enough for most existing SLR stations (including SLR2000) to detect. This implies that there must soon be prediction procedures and formats in place for the moon, other solar system bodies, and transponders in transit.

This document is the result of an effort to combine the prediction requirements of these various ranging techniques into a single laser ranging prediction format. The format presented is the standard for laser ranging as of mid-2006. It will undoubtedly undergo some changes over the years as we gain experience with some of the more exotic targets.

Format Features

1.No Euclidean Space Assumptions
The range to the environs of the moon and beyond cannot be simply calculated from the square root of the sum of the squares of the reflector's topocentric x, y, and z coordinates. The movement of the earth and moon during the approximately 2.5 second round trip is large enough that the range must be computed as the sum of the iteratively determined lengths of the outbound and inbound legs. Because of the

distances and masses involved, there is also a non-negligible relativistic correction. The difference between the true range and the Euclidean distance gives a range error for the moon of a few to hundreds of microseconds. Omitting the relativistic correction causes a range error of about 50 nsec. Stellar aberration effects on pointing need to be considered since the aberration is a second or two of arc at the moon, 30 or more arcseconds for Mars and asteroids, and possibly more for close-in spacecraft in transit.

The orbits of the moon and other major solar system objects can not be integrated easily on site in the way artificial earth satellites can. However, one can readily interpolate tables of geocentric coordinates for these and the other laser targets. The tabular format also benefits lower earth satellite ranging by removing the need to tune the predictions to a particular integrator. In addition, other non-integrable functions such as drag and orbital maneuvers can be included with a tabular format.

2.Multiple records

The tabular format will need to include at least x, y, z and a corresponding time for each ephemeris entry. This and other specialized information will be spread over several records, the number and type depending on altitude and target class. The time between each entry will normally be constant and will be small enough to meet any reasonable precision requirements using the supplied interpolation software. The time should be large enough to avoid excessive file size. Typical values are 1 minute for low earth satellites, 15 minutes at the moon, and hours or longer for the planets. See the section **Interpolator Definition** below for more information.

Record pairs like position 10, direction 1 and 2, and corrections 30, directions 1 and 2 should be treated as sets. For a transponder or any other target for which the time between entries is less than the round-trip light time, records 10 directions 1 and 2, etc. must be grouped so that the fire and receive legs follow each other in the file. In other the words the records are not in strict time order. See the transponder example in Appendix B.

3.Variable entry spacing

To accommodate high eccentricity satellites like LRE, variable entry spacing is a possibility that is permitted in the format and the sample interpolator.

4.Line length limits and method of transmission

The file headers have a maximum length at this time of 82 characters. "Deep space" targets may require position records longer than this. No mode of distribution is assumed, so email, ftp, and scp should be usable.

5. Free format read, fixed format write

Due to the large dynamic range in the target positions and velocities, the non-header data should be read in free format. The prediction providers should write with a fixed format so that all fields line up for a given satellite. Doing so will allow easy visual reading of the files for debugging. White space (at least one space) is required between fields to clearly separate them.

The format in appendix A show width and significant digits for each field. For the free format records, this represents typical width for planning purposes.

6. True body fixed system of date and earth rotation parameters

The coordinate system used in the TIRV's is pseudo-body-fixed. The new format is usually presented in the true-body-fixed of date system. (We also use the term International Terrestrial Reference Frame – ITRF). In this reference system, the earth's pole positions have been included in the predicted positions. Earth Orientation Parameters (EOP's), x-pole and y-pole, were included in the TIRV files to allow rotation from pseudo-body-fixed to true-body-fixed system to be computed at the individual ranging stations. This was done when prediction sets were often created up to a year in advance for use in ranging systems at remote locations. Since fresh EOP's are now easily available to the prediction suppliers and since the predictions are usually supplied daily via the internet, there is no need to apply the EOP information on site, nor to back out values that may have been used in the predictions. In addition, the excess length of day was rarely used at the ranging stations. Earth orientation information will only be supplied in the case of predictions that are presented in the inertial (space-fixed) reference system.

7. Multiple days per file

As with current IRVs distribution practices, the prediction file for a particular satellite will contain several days worth of data. This should help interpolating over day boundaries, which could otherwise cause problems. Header records appears only once per file.

8. Integration past end of file

Current IRVs permit integration well past the epoch of the last IRV in a prediction set. This benefits stations that are cut off from a supply of IRVs for a moderate period of time. The predictions show steadily increasing runoff, but can still allow data to be taken, especially with higher satellites. In addition, it is also possible to extend the integrations several months into the future for the purpose of scheduling. The latter use has fairly low accuracy requirements. It should be possible for the site to integrate the last state vector in a prediction file for some time into the future. (Targets on or orbiting the moon and planets can not be handled in this way.) Software could be written to convert the last state vector into a TIV file, which then could be input to the existing scheduling software. This will not help with other targets, however, and the lack of tuning in the CPF state vectors will reduce the accuracy of the extrapolation. Given that the extrapolation is only used for scheduling, this should not be a serious problem.

9. Elimination of drag and maneuver messages
Since the drag information can be built into the tabular state vectors, there should be no need for separate drag messages. Drag could not be easily incorporated into tuned IRVs.

Maneuvers will also be built into the CPF files. Therefore, maneuver messages will only be needed to warn stations of the event.

10. Compression
Common compression software such as compress, gnu zip, and others could be used to reduce the CPF files sizes for distribution. Thus far, the files have been of a manageable size and have not required compression even with email distribution.

11. File naming conventions
While there appears to be a wide range of file naming conventions used, the following is required for the new prediction format:
  satellite_cpf_yymmdd_nnnv.src
  where the fields are as follows:
    - satellite:
        •Official satellite name (See table in Appendix C and the up-to-date list at http://ilrs.gsfc.nasa.gov/products_formats_procedures/satellite_names.html.)
        •hyphens are allowed, but no blank spaces
        •variable length, maximum 10 characters

- nnn:
    - ●ephemeris version number. This is day of year + 500 to distinguish CPFs from TIVs in time bias and other messages. The "500" can be dropped when TIVs are discontinued. This field is three digits with zero leading fill.
- v:
    - ●version within the day. This is one digit, starting with '1'.
- src:
    - ●prediction provider code, 3 characters long.

Format Field Comments

1.SIC, NORAD and COSPAR ID's and satellite name
   SIC, COSPAR, and NORAD IDs and satellite name will be included in the prediction headers as a convenient cross reference. Satellite names should be taken from the standard list in Appendix C.

2.Center of mass to reflector offset
   The position vectors of spherical satellites always refer to the satellite's center of mass. An optional record H5 can indicate the range correction from the center of mass to the reflector reference radius. If H5 is given the stations can correct the interpolated two-way range station-satellite station from the center of mass to the reflectors by subtracting twice this correction.

   Position vectors of non-spherical, attitude-controlled satellites can either be given for the center of mass (center of mass correction flag in header record H2 set to '0') or the reflector reference point (correction flag set to '1'). As the stations usually do not know the attitude of the satellites no action is required in either case.

   As GNSS satellites (GPS, GLONASS, Galileo) are seen from the Earth's surface within a small angle only, reflector corrections could be given as an approximate radial correction in header record H5 if the given positions refer to the center of mass.

3.Estimated accuracy
   These records give an estimate of the expected accuracy (peak-to-peak) at certain points during the day. This will be based on the experience of the prediction provider. The intention is to use this information to suggest or automatically set a station's range

gate. This will be especially valuable to automated stations so that excessive time is not spent in searching for an optimal range gate and tracking settings.

4. Leap second

Application of leap seconds has always been a source of some confusion. In the new format, each ephemeris record contains a leap second value. In prediction files spanning the date of a leap second, those records after the leap second will have this flag set to the number of leap seconds (always '1' so far, but standards allow for -1). In other words, a 3-day file starting the day before a leap second is introduced will have the leap second flag set to '0' for the first 24 hour segment and '1' in the last 48 hours.

Even though the flag is non-zero, the leap second is not applied to the CPF times or positions. The station software needs to detect the leap second flag and handle the time argument to the interpolator appropriately.

Prediction files could still have the leap second flag set to non-zero for several days after the leap second has been introduced.

Once the leap second flag returns to '0' after introduction of the leap second, stations still running on the old time system have to take into account the leap second.

Normally, the leap second field will be set to '0'.

5. Position and velocity fields

Artificial earth satellites will not include light time iteration corrections. These 10-0 records give the position vector corresponding to the same (common) epoch at the geocenter and satellite. For any CPF computed using a solar system ephemeris (e.g. DE-403), the 10-1 and 10-2 records are used and contain the light time iteration. For these the vector spans fire time at the geocenter to bounce time at the target(10-1) and from bounce time to return time at the geocenter (10-2).

The signs of corresponding elements in the outgoing and incoming positions fields will have opposite signs. The same is true with the velocities.

6. Correction fields

As noted above, several complications arise in predicting ranges and point angles of solar system targets. These are essentially relativity and aberration. The aberration can be broken into light-time aberration which applies to all targets and stellar aberration

which applies to those targets (such as moon and planets) which are computed from solar system ephemerides. Near-earth artificial satellites are usually computed in the geocentric system and do not require the so-called stellar aberration. Light time aberration is already applied implicitly in the state vectors supplied in the new format. Stellar aberration corrections are applied in computing point angles on site, while the relativistic corrections are applied to the ranges. ESAA, pp 127-130.

The in-bound and out-bound relativistic corrections are due to geodesic curvature. The time-scale correction converts a solar system barycentric range (elapsed time) into an elapsed time which would be observed at a station. This correction can be 200 m for a round trip range to Mars and is necessary because the vectors are computed in the solar system barycentric frame using a solar system ephemeris. The geodesic correction is included in the format while the time-scale correction is site-dependent and is computed in the sample on-site code. See ESAA.

If there are outgoing and incoming correction records, the corresponding aberration and relativity fields will have opposite signs. If there is only one correction record, it will be the '30' record with direction = '1', and the software must sense this and set the incoming aberration values as negative of outgoing ones. For point angle computations, the aberration values are added to the corresponding velocity values, and the result is converted to topocentric coordinates. (Aberration must not be added to the position as part of the range computation!)

The relativistic corrections are both positive, scalar values. These are added to the range based on the vector distances calculated from the outgoing and incoming positions. Again, if there is only one correction record, the relativistic correction will need to be doubled for the round trip range. An additional 0.27 nsec can be added to the round-trip range as an earth-moon geodesic curvature correction. The resulting range with relativistic corrections is then scaled from proper to coordinate time.

7. Lunar fields

Lunar predictions may include lunar features for offset pointing. These features do not have SIC or COSPAR IDs since they are not ranging targets. The ID for these objects will be given bogus IDs, perhaps negative numbers. A list of targets, names, and IDs will be supplied.

The libration vector (Euler angles ϕ,θ,ψ) and Greenwich apparent solar time are available in the "rotation angles" record, type 60, for the center of the moon file (SIC = 0099). This allows a station to compute point angles to any arbitrary lunar surface feature whose selenocentric coordinates they supply. Stations without arcsecond level pointing accuracy may need this as a basis for offset pointing to the reflectors. Ranges computed in this way will not be accurate enough for ranging (some station-dependent corrections have been left out).

To determine the pointing angles using the lunar Euler angles, the center of moon to center of earth vector is translated to the laser station coordinates using light time iteration. The aberration corrections are then added to this vector. The new aberrated body fixed coordinates are then rotated through the negative of the Greenwich apparent sidereal time. To this is added the result of creating the libration matrix from the rotation vector of (ϕ,θ,ψ) (Skip Newhall, private correspondence; see sample code) and premultiplying it by the station coordinate vector (x,y,z). This gives the inertial coordinates of the lunar feature. This vector is then rotated through the Greenwich apparent sidereal time to give the body fixed ranging station to feature vector of date, which can then be converted to RA/Dec, then HA/Dec, and then azimuth/elevation. If the lunar positions and velocities are supplied in inertial coordinates (reference frame = 1), the first rotation, through -GAST, is unneeded.

8. Transponder fields

Transponders can either be synchronous or asynchronous. Synchronous transponders fire when a laser pulse has been received from a ground station. The delay between receiving and transmitting the return pulse must be accounted for in both the prediction and data flow. Asynchronous transponders fire continuously for some period of time, as does the ground station. Both the spacecraft and ground station record transmit and receive time based on a local clock, which must be tied with an offset and rate to a master clock.

Transponders need various time, frequency and range rate fields in the format. With the exception of the oscillator relativity correction, these are slowly changing with time, so they can be included in the data header records. (Alternatively, some quantities could be distributed in separate files.) These fields are as follows.
- Pulse Repetition Frequency (PRF) - 1×10^{-5} to 1×10^{6} Hz
    - Asynchronous transponders only.
- Transponder transmit delay - 10sec to 1 msec

- •Synchronous transponders: delay between receive and fire
- •Asynchronous transponders: delay between fire command and fire
- •Transponder UTC offset - 10 nsec to 1 second
  - •Asynchronous transponders only
- •Oscillator Frequency Drift - 1 part in 10^{12} -10^{15}/day
  - •Asynchronous Transponders orbiting a solar system body
  - •Corrects for the drift of the satellite's on-board oscillator.
- •Relativity Correction to Satellite Oscillator Time Scale for 1 Way Range Rates - 1.5m/sec - 1cm/sec (5 nsec/sec - 0.03 nsec/sec)
  - •Asynchronous Transponder orbiting a solar system body
  - •Corrects for range rate change due to satellite orbiting in a different gravitational field.
- • Range rate is also needed to an estimated accuracy of 15 cm/sec, but this is computable from positions and/or velocities given a small enough time between vectors (5-10 sec).

As with lunar ranging, it may be necessary to compute point angles and range based on rotation angles of a planet or moon. While it is convenient and very accurate to use Euler angles for the moon, the universal system adopted by the IAU/IAG/COSPAR Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites uses the right ascension and declination of the body's pole as well as the position of the body's prime meridian (a_0, d_0, and W). See Davies or the ESAA for more details. These quantities also have a place in the new prediction format as do x, y, and z offsets from the center of the main body (e.g., a planet).

Interpolator Definition

The baseline for interpolation of the new format predictions will be a 10 point (9th order) Lagrange interpolation algorithm that allows for variably spaced record times. A sample interpolator has been written to accompany the new format. Recent investigations of study group members show the following record spacing to be reasonable, using position (X, Y, and Z) only. Note that the MGS (Mars Global Surveyor) results are identical with the step size of the Integration of the satellite's orbit. If the target had been on Mars, the interval would have been much larger.

Satellite	Interval (min)	
	Degree 7	Degree 9
	(8 point)	(10 point)

CHAMP (LEO)	2	3
GFO-1	3	4
TOPEX	4	5
LAGEOS	5	10
GPS	15	30
Moon	30	60
MGS at Mars	-	0.3

It is anticipated that the ranging stations could use a variety of interpolation schemes, preferably Lagrange. (Splines are strongly discouraged.) However, the baseline is the 10 point Lagrange interpolation and a maximum error due to production and interpolation of the predicted ephemeris of less than 1 nsec in range. To be conservative, prediction providers should use the intervals above for the 8 point interpolation. Any alternate interpolation scheme must provide 1 nsec agreement using a grid no narrower than the above. Interpolation must always be done in Cartesian (X, Y, Z) space and not in range/point angles for acceptable accuracy. The interpolation time must be between the middle 2 points of the interpolation series for maximum accuracy (i.e., between the 5th and 6th points of a 10 point interpolator). See Abramowitz and Stegun for details.

Sample code

Sample station implementation code incorporating the new interpolator has been developed and will be supplied in FORTRAN and C. This computer software handles the computation of topocentric ranging predictions rigorously for artificial satellites near or distant, the moon, and other solar system bodies. Targets computed from a geocentric ephemeris and those computed using a solar system barycentric ephemeris (moon, planets, satellites of either) must be handled differently, but the software package will call those routines necessary based on target. See appendix D for more details.

Constants

The speed of light used by both prediction centers and stations should be the IERS Convention 20003 standard of 299792458 m/sec. Site coordinates should be in the International Terrestrial Reference Frame (ITRF). Although JPL's DE-403 ephemeris is not, the differences are not significant for predictions and normal point formation. Lunar reflector coordinates are usually supplied by the creators of the ephemeris and are the result of fitting the ranging data.

Conclusion

The requirements established for this study group for improved prediction accuracy and inclusion of exotic targets is met through the ILRS tabular prediction format. The new format covers 4 different target types in one prediction format and sample software set. It opens up opportunities for most stations to range a wider variety of targets and will naturally solve several difficulties in current SLR predictions. The format will come at the expense of some software retooling and larger file transfers. It will, however, provide a flexible platform for laser ranging predictions into the foreseeable future.

Study Group

This format is the result of combined efforts by the study group members:

- R. Ricklefs, chair, University of Texas/McDonald Observatory, and CSR
- J. McGarry, co-chair, NASA/Goddard Space Flight Center
- G. Appleby, NERC Space Geodesy Facility
- G. Bianco, Agenzia Spaziale Italiano
- C. Clarke, Honeywell Technology Solutions, Inc.
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- J. Luck, Electro Optic Systems
- D. McClure, Honeywell Technology Solutions, Inc.
- C. Moore, Electro Optic Systems
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- U. Schreiber, Technical University of Munich
- R. Wood, NERC Space Geodesy Facility
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- T. Yoshino, Communications Research Laboratory

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Appendix A. Prediction Format Version 1.00/1.01

1) Data headers

Header type 1 Basic information - 1 (required)

1-2	A2	Record Type (= "H1")
4-6	A3	"CPF"
8-9	I2	Format Version
12-14	A3	Ephemeris Source (e.g., "HON", "UTX ")
16-19	I4	Year of ephemeris production
21-22	I2	Month of ephemeris production
24-25	I2	Day of ephemeris production
27-28	I2	Hour of ephemeris production (UTC)
31-34	I4	Ephemeris Sequence number
36-45	A10	Target name from official list (e.g. lageos1)
47-56	A10	Notes (e.g., "041202","DE-403")

Header type 2 Basic information - 2 (required)

1-2	A2	Record Type (= "H2")
4-11	I8	COSPAR ID
13-16	I4	SIC
18-25	I8	NORAD ID
27-30	I4	Starting Year
32-33	I2	Starting Month
35-36	I2	Staring Day
38-39	I2	Starting Hour (UTC)
41-42	I2	Starting Minute (UTC)
44-45	I2	Starting Second (UTC)
47-50	I4	Ending Year
52-53	I2	Ending Month
55-56	I2	Ending Day
58-59	I2	Ending Hour (UTC)
61-62	I2	Ending Minute (UTC)
64-65	I2	Ending Second (UTC)
67-71	I5	Time between table entries (UTC seconds)(=0 if variable)
73	I1	Compatibility with TIVs = 1 (=> integrable, geocentric ephemeris)

75	I1	Target type

    1=passive (retro-reflector) artificial satellite

    2=passive (retro-reflector) lunar reflector

    3=synchronous transponder

    4=asynchronous transponder

77-78 I2   Reference frame

    0 =geocentric true body fixed (default)

    1=geocentric space fixed (i.e. Inertial) (True of Date)

    2=geocentric space fixed (Mean of Date J2000)

80   I1   Rotational angle type

    0= Not Applicable

    1= Lunar Euler angles: ϕ, θ, and ψ

    2 = North pole Right Ascension and Declination, and angle
         to prime meridian (α_0, δ_0, and W)

82   I1   Center of mass correction

    0= None applied. Prediction is for center of mass of target

    1= Applied. Prediction is for retro-reflector array

Header type 3 Expected accuracy

1-2	A2	Record Type(="H3")
4-8	I5	Along-track run-off after 0 hours (meters)
10-14	I5	Cross-track run-off after 0 hours (meters)
16-20	I5	Radial run-off after 0 hours (meters)
22-26	I5	Along-track run-off after 6 hours (meters)
28-32	I5	Cross-track run-off after 6 hours (meters)
34-38	I5	Radial run-off after 6 hours (meters)
40-44	I5	Along-track run-off after 24 hours (meters)
46-50	I5	Cross-track run-off after 24 hours (meters)
52-56	I5	Radial run-off after 24 hours (meters)

Header type 4 Transponder information

1-2	A2	Record Type (= "H4")
4-15	F12.5	Pulse Repetition Frequency (PRF) in Hz
17-26	F10.4	Transponder transmit delay in microseconds
28-38	F11.2	Transponder UTC offset in microseconds
40-50	F11.2	Transponder Oscillator Drift in parts in 10^{15}

Header type 5 Spherical satellite center of mass correction

1-2   A2   Record Type (= "H5")

4-10   F7.4   Approximate center of mass to reflector offset in meters (always positive)

Header type 9 End of header (Last header record)

1-2   A2   Record Type (= "H9")

2)Ephemeris entry (repeat as needed)

   NOTE: ALL fields MUST be separated by spaces, since these records are read free format. The field widths (e.g., I5, f12.5) are suggestions, and should be sized according to the target's needs.

Record type 10 Position

   1-2   A2   Record Type (= "10")

          I1   Direction flag[*] (common epoch = 0; transmit = 1; receive = 2)

          I5   Modified Julian Date (MJD)

          F13.6   Seconds of Day (UTC) (Transmit or receive)

          I2   Leap second flag (= 0 or the value of the new leap second)

          F17.3   Geocentric X position in meters

          F17.3   Geocentric Y position in meters

          F17.3   Geocentric Z position in meters

Record type 20 Velocity

   1-2   A2   Record Type (= "20")

          I1   Direction flag[*] (common epoch = 0; transmit = 1; receive = 2)

          F19.6   Geocentric X velocity in meters/second

          F19.6   Geocentric Y velocity in meters/second

          F19.6   Geocentric Z velocity in meters/second

Record type 30 Corrections (All targets computed from a solar system ephemeris)

   1-2   A2   Record Type (= "30")

          A1   Direction flag (common epoch[*] = 0;transmit = 1; receive = 2)

          F18.6   X stellar aberration correction in meters

F18.6 Y stellar aberration correction in meters

F18.6 Z stellar aberration correction in meters

F5.1   Relativistic range correction in nsec (positive number)

Record type 40 Transponder specific (Transponders)

1-2	A1	Record Type (= "40")
	F6.3	Oscillator relativity correction in meters/second

Record type 50 Offset from center of main body (Surface features and satellites)

1-2	A2	Record Type (= "50")
	I1	Direction flag (bounce=0; transmit = 1; receive = 2)
	I5	Modified Julian Date (MJD)
	f13.6	Seconds of Day (UTC)
	a10	Name of target (no spaces in middle)
	f17.3	X position offset in meters
	f17.3	Y position offset in meters
	f17.3	Z position offset in meters

Record type 60 Rotation angle of offset (Surface features)
(See Rotation Angle Type in header record 2.)

1-2	A2	Record Type (= "60")
	I5	Modified Julian Date (MJD)
	F13.6	Seconds of Day (UTC)
	F17.12	Rotation angle 1 in degrees (For moon: ϕ)
	F17.12	Rotation angle 2 in degrees (For moon: θ)
	F17.12	Rotation angle 3 in degrees (For moon: ψ)
	F17.12	Greenwich Apparent Sidereal Time in hours

Record type 70 Earth orientation (For space-fixed mode,
as needed, typically once a day)

1-2	A2	Record Type (= "70")
	I5	Modified Julian Date (MJD)
	I6	Seconds of Day (UTC)

F8.5   X pole (arcseconds)

F8.5   Y pole (arcseconds)

F10.6   UT1-UTC (seconds)

Record type 99 Ephemeris Trailer (last record in ephemeris)

1-2   A2   Record Type (= "99")

3) Comments

1-2   A2   Record Type (= "00")

3-80 A   Free format comments

[*] Direction flag has the following meanings (see Appendix C):

• Common epoch (0): instantaneous vector between geocenter and target, without light-time iteration. This epoch is the same as found on corresponding TIVs.

• Transmit (1): position vector contains light time iterated travel time from the geocenter to the target at the transmit epoch.

• Receive (2): position vector contains light time iterated travel time from the target to the geocenter at the receive epoch. (The sign of each element is opposite that of the transmit vector.)

Appendix B - Sample Prediction Configurations

Note: the number after the hyphen in the typical configurations below refer to the direction indicator, 1 for outbound, 2 for inbound.

1. Earth-orbiting artificial satellites

A typical record configuration for most satellite is the following.

H1 H2 H3 H9 10-0 10-0 10-0 ... 99

Mandatory records: H1, H2, H9, 10-0, 99.

Example:
```
H1 CPF  1  AIU 2005 11 16  4  8201 gps35
H2  9305401 3535     22779 2005 11 15 23 59 47 2005 11 20 23 29 47   900 1 1  0 0 0
H9
10 0 53689   86387.000000  0  -13785362.868 -12150743.695  19043830.747
10 0 53690     887.000000  0  -13656536.158 -14288496.731  17628980.237
10 0 53690    1787.000000  0  -13618594.073 -16250413.260  15908160.431
10 0 53690    2687.000000  0  -13647177.924 -18001187.561  13911910.138
10 0 53690    3587.000000  0  -13712868.344 -19511986.614  11675401.577
10 0 53690    4487.000000  0  -13782475.931 -20761369.576   9237779.852
...
99
```

2. Lunar reflectors

For lunar reflectors, a typical sequence of records would be as follows. Note that the '30-2' record is not really needed for the moon. The aberration corrections are not needed unless the orbit is computed relative to a solar system ephemeris, as the moon is.

H1 H2 H3 H9 10-1 10-2 30-1 30-2 10-1 10-2 30-1 30-2 10-1 10-2 30-1 30-2 ... 99

Mandatory records: H1, H2, H9, 10-1, 10-2, 30-1, 99.

Example:
```
H1 CPF  1  UTX 2005 11 16 14  8201 apollo15   jpl_de-403
H2       103    103        0 2005 11 17  0  0  0 2005 11 21 23 45  0   900 0 2  0 0 0
H9
10 1 53691     0.0 0    343226579.261     46543054.740     166061912.378
10 2 53691     0.0 0   -343237287.411    -46403753.013    -166044491.398
30 1   -7566.  36724.   5545.  25.5
10 1 53691   900.0 0    345427390.701     24820813.890     166269371.365
10 2 53691   900.0 0   -345429119.195    -24681112.863    -166251952.876
30 1   -5221.  37124.   5504.  25.5
10 1 53691  1800.0 0    346255366.913      3006463.995     166475893.820
10 2 53691  1800.0 0   -346248108.749     -2866942.040    -166458477.824
30 1   -2855.  37375.   5463.  25.5
```

```
...
99
```

For the center of the moon, the libration information needs to be carried along.

> H1 H2 H3 H9 10-1 10-2 30-1 30-2 60 10-1 10-2 30-1 30-2 60 10-1 10-2 30-1 30-2 60 ... 90

Mandatory records: H1, H2, H9, 10-1, 10-2, 30-1, 60, 99.

Example:
```
H1 CPF  1  UTX 2005 11 16 14  8201 luncenter  jpl_de-403
H2      99   99        0 2005 11 17  0  0  0 2005 11 21 23 45  0   900 0 2  0 1 0
H9
10 1 53691     0.0 0      344918986.877       46883148.021      165882903.645
10 2 53691     0.0 0     -344929799.893      -46742993.132     -165865415.671
30 1  -7566.  36724.  5545.  25.5
60 53691     0.0   -0.762524039740   21.927815073381   242.085911540111
3.743252931977
10 1 53691   900.0 0      347138025.698       25052846.263      166090930.914
10 2 53691   900.0 0     -347139804.259      -24912287.206     -166073445.455
30 1  -5221.  37124.  5504.  25.5
60 53691   900.0   -0.762477162557   21.927762020202   242.223125654342
3.993937427448
10 1 53691  1800.0 0      347977335.938        3129493.252      166298018.604
10 2 53691  1800.0 0     -347970072.850       -2989111.915     -166280535.662
30 1  -2855.  37375.  5463.  25.5
60 53691  1800.0   -0.762430689795   21.927708977647   242.360340162630
4.244621923024
...
99
```

or (for inertial systems)

> H1 H2 H3 H9 10-1 10-2 30-1 30-2 50 60 10-1 10-2 30-1 30-2 50 60 10-1 10-2 30-1 30-2 50 60 ... 99

3. Asynchronous Transponders
A typical record sequence would be the following.

> H1 H2 H3 H4 H9 10-1 10-2 30-1 30-2 40 10-1 10-2 30-1 30-2 40 10-1 10-2 30-1 30-2 40... 99

Mandatory records: H1, H2, H4, H9, 10-1, 10-2, 30-1, 30-2, 40, 99.

Example:

```
H1 CPF  1  GSC 2004 03 30 12   901 lro
H2 99999999 9999 99999999 2004 04 04 00 00 00 2004 04 04 05 00 00    10 0 4  0 0 0
H3     0     0     0     1     0     0     5     1     1
H4   1999.91715   273.1500     2004.93       15.30
H9
10 1 53098   84449.02096     -125015785900.315 -238593151366.328  113777817699.433
10 2 53099       0.00000     -157578821821.085 -218511517400.466  113800334257.752
20 1         -4900.351123       27002.440493      -11504.716991
20 2         -1033.856498       27424.269894      -11503.554375
30 1     14960874.918060   -6906109.317657    1955191.986389   19356.3
30 2    -13838706.981995    8961558.044586   -1956244.853897   19361.8
40  0.1000
10 1 53098   84459.01980     -125189460917.443 -238502228781.030  113777934456.549
10 2 53099      10.00000     -157737908754.342 -218396877560.796  113800451035.803
20 1         -4880.719560       27005.997166      -11504.711036
20 2         -1013.916777       27425.015665      -11503.548412
30 1     14955868.474579   -6917009.332855    1955188.391006   19356.3
30 2    -13832201.994965    8971645.220612   -1956241.253082   19361.8
40  0.1000
10 1 53098   84469.01863     -125363069927.043 -238411179620.121  113778051444.382
10 2 53099      20.00000     -157896912383.972 -218282121726.361  113800568044.534
20 1         -4861.085417       27009.539567      -11504.705081
20 2          -993.976518       27425.746937      -11503.542448
30 1     14950854.096252   -6927905.739502    1955184.780594   19356.3
30 2    -13825689.658722    8981727.696381   -1956237.637238   19361.9
40  0.1000
...
99
```

4. Synchronous Transponders

A typical record sequence would be:

> H1 H2 H3 H4 H9 10-1 10-2 30-1 30-2 10-1 10-2 30-1 30-2 10-1 10-2 30-1 30-2
> ... 99

Mandatory records: H1, H2, H4, H9, 10-1, 10-2, 30-1, 30-2, 99.

Example:

```
H1 CPF  1  GSC 2004 03 30 12   901 xponder1
H2 99999999 9999 99999999 2004 04 04 00 00 00 2004 04 04 05 00 00    10 0 3  0 0 0
H3     0     0     0     1     0     0     5     1     1
H4      0.00000   273.1500        0.00         0.00
H9
10 1 53098   84449.02096     -125015785900.315 -238593151366.328  113777817699.433
10 2 53099       0.00000     -157578821821.085 -218511517400.466  113800334257.752
20 1         -4900.351123       27002.440493      -11504.716991
20 2         -1033.856498       27424.269894      -11503.554375
30 1     14960874.918060   -6906109.317657    1955191.986389   19356.3
30 2    -13838706.981995    8961558.044586   -1956244.853897   19361.8
10 1 53098   84459.01980     -125189460917.443 -238502228781.030  113777934456.549
10 2 53099      10.00000     -157737908754.342 -218396877560.796  113800451035.803
20 1         -4880.719560       27005.997166      -11504.711036
20 2         -1013.916777       27425.015665      -11503.548412
30 1     14955868.474579   -6917009.332855    1955188.391006   19356.3
30 2    -13832201.994965    8971645.220612   -1956241.253082   19361.8
10 1 53098   84469.01863     -125363069927.043 -238411179620.121  113778051444.382
10 2 53099      20.00000     -157896912383.972 -218282121726.361  113800568044.534
20 1         -4861.085417       27009.539567      -11504.705081
```

```
20 2             -993.976518        27425.746937         -11503.542448
30 1      14950854.096252      -6927905.739502       1955184.780594    19356.3
30 2     -13825689.658722       8981727.696381      -1956237.637238    19361.9
...
99
```

Appendix C - How to Create Consolidated Prediction Format Files: A Cookbook

At the Laser Workshop in Eastbourne in October, 2005 the ILRS Governing Board set the goal of converting all stations from the Tuned Inter-range Vectors (TIVs) to the new Consolidated Predictions Format (CPF) by June 31, 2006. All prediction centers are expected to start providing the CDDIS and EDC with CPF files on a routine basis by the end of 2005. This conversion is the culmination of 5 years of work by the ILRS Prediction Format Study Group. The new format promises to provide better prediction accuracy for artificial satellites, especially LEOs, as well as providing a common system that will include lunar retro-reflectors and transponders in lunar orbit and beyond.

This short document summarizes the main requirements for producing CPF files. There is a more complete and extensive document that discusses philosophy and format details. It can be found at the addresses listed in the **Resources** section.

SLR Predictions (Earth orbiting satellites))

1)CPF predictions are tabulated satellites state vectors in the geocentric earth-fixed coordinate system of date known as ITRF (International Terrestrial Reference Frame).

2)The state vectors are generated from predicted orbits based on the best possible force models (gravity field, air drag, solar pressure, ...) and predicted earth rotation parameters. No tuning is performed.

3)CPF files are generated at least on a daily basis, containing a data span of five days. The prediction center should re-issue prediction files for low satellites several times per day, if necessary.

4)When interpolated with an 10 point Lagrange interpolator, a CPF file must duplicate the output of the prediction orbit to ± 0.5 nanoseconds in range. Separations of tabular records for various altitudes of satellites are included below.

5)Fill all fields in the records you write. Headers are fixed format. Body records are free format (after the 2 digit record identification) with at least 1 space between fields. For a specific target, the fields in the body records should line up, for easy reading by humans.

6)Required records: Headers H1, H2, and H9. Header H3 is optional. Header H4 is for use with spherical satellites only. Data record 10 with direction '0' (instantaneous vector between geocenter and satellite at fire time) and 99 are required. None of the rest pertain.

7)The interpolator must always interpolate in the center interval of a 10 point span. Therefore, include at least 5 points prior to file generation/distribution time to prevent stations from trying to interpolate outside the optimal interval.

8)Each ephemeris record contains a leap second value. In prediction files spanning the date of a leap second, those records after the time of the leap second will have this flag set to the number of leap seconds (always '1' so far, but standards allow for -1). In other words, a 3-day file starting the day before a leap second is introduced will have the leap second flag set to '0' for the first 24 hour segment and '1' in the last 48 hours.

Even though the flag is non-zero, the leap second is not applied to the CPF times or positions. The station software needs to detect the leap second flag and handle the time argument for the interpolator appropriately.

Prediction files starting at 0 hours immediately after the leap second has been introduced will have the leap second flag set to '0'.

Normally, the leap second flag will be set to '0'.

9)CPF files should be named in accordance with the following format:
  satellite_cpf_yymmdd_nnnv.src
  where:
    - satellite:
        = Official satellite name (See table below.)
        = hyphens are allowed, but no blank spaces
        = variable length, maximum 10 characters
    - nnn:
        = ephemeris version number. Day of year + 500 to distinguish CPF from TIV in
           time bias and other messages. The "500" can be dropped when TIVs
            are discontinued. This field is three digits with zero leading fill.
    - v:
        = version within the day. One digit, starting with '1'.
    - src:

= prediction provider code. Three characters.

10)If predictions are emailed, the subject line should read:
    Subject: satname DAILY CPFS center,
    e.g., SUBJECT: ICESAT DAILY CPFS UTX .
  The file should be mailed as embedded text, not as an attachment.

11)Maneuvers messages are no longer needed except to alert operators.

12)CPF files should normally be ftp-ed to EDC or CDDIS for distribution, as detailed in their instructions.

13)There is a sample software program called cpf_chk that can be used to test the CPF files' format. Using this program could save a great deal of time in hand-checking the prediction files. The code is provided as-is, and any bug fixes or improvements will be gratefully accepted.

14)Format Version Numbers: Only the integer portion should be used. For example, version 2.34 would be entered as '2'. All versions from n.00 to n.99 would be backward compatible.

Predictions for the Moon and other bodies requiring a solar system ephemeris

1)Follow the same procedures as for "SLR Predictions" with the following differences.

2)The out-bound and in-bound leg vectors (records 10-1 and 10-2) are corrected for light time. In other words, for record 10-1, the vector spans from the geocenter at fire time to target position at bounce time. Similarly, for record 10-2, the vectors spans from the target at bounce time to the geocenter at return time.

3)For the moon and transponders, time of prediction is fire time for the outbound leg and return time for in-bound leg. The latter is for reference only. For rotation records (30), the time is bounce time (i.e., firing time + out-bound leg length). Out- and in-bound leg and rotation records remain together in fire time order.

4) The in-bound leg is required for ranging to the moon and beyond or any other orbit that has been computed using a solar system ephemeris.

5) Position, velocity, and aberration vector elements have opposite signs on out-bound and in-bound leg records. Relativistic corrections are always positive and additive. When there is only one corrections record (type 30) for each outbound/inbound leg pair, the relativistic correction must be one-way, as it will be added twice.

6) Include the following records:
- •Lunar reflectors: H1, H2, H9, 10-1, 10-2, 30-1, 99
- •Center of moon: H1, H2, H9, 10-1, 10-2, 30-1, 60, 99
- •Asynchronous transponders: H1, H2, H4, H9, 10-1, 10-2, 20-1, 20-2, 30-1, 30-2, 40, 99
- •Synchronous transponders: H1, H2, H4, H9, 10-1, 10-2, 30-1, 30-2, 99

Resources

1) Standard Satellite Prediction Spacing

Satellite class	Interval (min)
CHAMP (LEO)	2
GFO-1	3
TOPEX	4
LAGEOS	5
GPS	15
Moon	30

2) Standard Laser Target Names

SLR Targets:

adeos	ers2
adeos2	etalon1
ajisai	etalon2
beaconc	fizeau
champ	geos3
diadem1c	gfo1
diadem1d	gfz1
envisat	glonass## (where ## is the 2-digit
ers1	GLONASS satellite number)

gpb	meteor3m msti
gps35	reflector
gps36	resurs
gracea	starlette
graceb	starshine2
icesat	starshine3
jason1	stella
lageos1	sunsat
lageos2	tips
larets	topex
lre	westpac
meteor3	zeia

LLR Targets:
apollo11
apollo14
apollo15
luna17
luna21
luncenter

An up-to-date list will be maintained at:
http://ilrs.gsfc.nasa.gov/products_formats_procedures/satellite_names.html

2. Full documentation
http://ilrs.gsfc.nasa.gov/products_formats_procedures/predictions/cpf.html

3.Sample Software

4.Enter http://ilrs.gsfc.nasa.gov/products_formats_procedures/predictions and select
CPF Sample Code. The appropriate file will be downloaded.

4. EDC and CDDIS upload instructions
Contact Carey Noll at carey.noll@nasa.gov or Wolfgang Seemueller at
seemuell@dgfi.badw-muenchen.de .

5. For reference, CPF files can be found at:
ftp://cddis.gsfc.nasa.gov/pub/slr/cpf_predicts or

ftp://www.dgfi.badw-muenchen.de/slr/cpf_predicts.

or contact Carey Noll (carey.noll@nasa.gov) to be added to the email exploder.

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6.CPF email exploder:

Contact Wolfgang Seemeuller (seemuell@dgfi.badw.de) or check the ILRS web page.

Appendix D - Consolidated Prediction Format User's Guide

At the Laser Workshop in Eastbourne in October, 2005 the ILRS Governing Board set the goal of converting all stations from the Tuned Inter-range Vectors (TIVs) to the new Consolidated Predictions Format (CPF) by June 31, 2006. All prediction centers are expected to start providing the CDDIS and EDC with CPF files on a routine basis by the end of 2005. This conversion is the culmination of 5 years of work by the ILRS Prediction Format Study Group. The new format promises to provide better prediction accuracy for artificial satellites, especially LEOs, as well as providing a common system that will include lunar retro-reflectors and transponders in lunar orbit and beyond.

This short document tries to summarize the main requirements for using CPF files. There is a more complete and extensive document that discusses philosophy and format details. It can be found at the addresses listed in the **Resources** section.

General comments
1)Sample software is provided at the address given at the end of this document. There are 'c' and FORTRAN versions of the CPF file reading and interpolation software (with test programs and "readme" files), a more advanced program for SLR-type predictions (CPF_INTER), and a more advanced program for lunar and transponder predictions (CPFPRED). In addition there is a CPF file format checker (cpf_chk) and a file to convert CPF files into untuned TIVs. It is expected that all this code will be supported. Note that bug fixes and improvements will be gratefully accepted. Treat this as an open source project where everyone making changes to the software contributes the improvement of the final product.

In addition, there is a suite of software to split a CPF file into shorter single pass files for a particular station and produce a schedule file. There is also a directory containing fragments of c++ code for reading and interpolating the CPF files. This software is for demonstration purposes only, and active maintenance is not anticipated.

Test input and output are supplied with all programs.

2)For acceptable precision, interpolate in Cartesian coordinates (body-fixed or inertial) and not in point angles and range. There is sample code to read and interpolate the CPF files, so you do not need to "re-invent the wheel."

3) Interpolated time must between the 5th and 6th points for 10 point interpolation, or precision will be degraded.

4) Due to rule 3), the interpolator needs 5 extra records at the beginning and end of a pass to maintain full prediction accuracy. The sample interpolator will produce a warning message and give the best results it can if there are not enough records to center on the time of interpolation.

5) Do not assume that the prediction file starts at 0 hours UTC.

6) It is a good practice to read all fields in as ASCII strings before converting to integers or floating point. With added checks, this will prevent software crashes when mis-formed or blank fields are encountered.

Resources

1. Full documentation

http://ilrs.gsfc.nasa.gov/products_formats_procedures/predictions/cpf.html

2. Sample Software

The software is organized into the following directories:as follows;

    common_c cpf_c   cpf_comb_c cpf_llr_c cpf_slr_c cpf_chk_c   cpf_sched
    common_f cpf_f   cpf_comb_f cpf_llr_f cpf_slr_f cpf_eos_cpp include
    cpf2irv_c

There are FORTRAN and c versions of most programs. Directory names ending in "_c" contain c code, directory names ending in "_cpp" contain c++ code, and directory names ending in "_f" contain FORTRAN.

    common_c, common_f -
            Routines are included that read a cpf file and interpolate it.
            Also, it contains additional routines needed by several of the
            programs listed below.

cpf_c, cpf_f -

>	These contain programs and standard input and output to test
>	the basic CPF read and interpolation software found in
>	common_c and common_f.

cpf_slr_c, cpf_slr_f -

>	Programs in these directories produce range and point angles
>	for slr predictions. Test input and output files are included.

cpf_llr_c, cpf_llr_f -

>	Programs in these directories produce range and point angles
>	for llr and transponders at the moon and beyond. Test input
>	and output files are included.

cpf_comb_c, cpf_comb_f -

>	Programs in these directories produce range and point angles
>	for slr, llr and transponders. Test input and output files
>	are included. This code is combines slr and llr code above
>	into one set of routines.
>>	>> NOT YET AVAILABLE <<

cpf_chk_c -

>	This contains a program to test cpf files for conformity with
>	the format standard. This is mainly designed for predictions
>	centers and their test stations. It can be installed in any
>	station with a feeling of paranoia.

cpf_eos_cpp -

>	C++ code fragments from EOS. See the Readme.doc file for an
>	explanation.

cpf_sched -

>	This directory contains a program to split a multi-day cpf
>	file into pass-by-pass files for a particular station. It
>	also contains programs to produce an eye-readable schedule
>	of the passes. Two programs are in FORTRAN and one is in c.

cpf2irv_c -
    This software converts a CPF file into a set of untuned IRVs.

include -
    Headers for FORTRAN and c programs can be found here.

Note that not all programs and routines are available in all languages. Currently, the only c++ routines are provided as code fragments and not as a full compilable package.

Priority for maintenance will be given to common_c, common_f, cpf_c, cpf_f, cpf_slr_c, cpf_slr_f, cpf_llr_c, cpf_llr_f, and include. The rest will be maintained as resources are available.

To download the sample code, enter http://ilrs.gsfc.nasa.gov/products_formats_procedures/predictions and select CPF Sample Code. The appropriate file will be downloaded.

3. CPF files can be found at:
ftp://cddis.gsfc.nasa.gov/pub/slr/cpf_predicts, or
ftp://www.dgfi.badw-muenchen.de/slr/cpf_predicts,
or contact Carey Noll (carey.noll@nasa.gov) to be added to the email exploder.

4.It is recommended that the stations use predictions from the primary providers for each satellite as listed at
http://ilrs.gsfc.nasa.gov/products_formats_procedures/predictions/prediction_centers.htm

l. Use backup providers when usable predictions are not available from the primary providers.
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MAXIMUM PREDICTIONS GRID SPACINGS
to achieve RSS due to INTERPOLATION ONLY of:
1 ns, and 10 ps, in RANGE
1 second of arc, in AZIMUTH and ELEVATION

J.McK. Luck
Research Fellow
Electro Optic Systems Pty.Ltd.

Table 1: Prediction Intervals giving nominated Interpolation Errors

Satellite	Maximum Grid Spacings (seconds) when using 8th-order Lagrange Interpolation				CPF Recommendation	
	RANGE		AZIMUTH	ELEVATION	Deg 7	Deg 9
	1 ns	10 ps	1 arcsec	1 arcsec		
CHAMP	234	127	441	456	120	180
STARLETTE	240	127	466	519	180	240
AJISAI	310	170	617	628	240	300
LAGEOS	501	280	1097	1118	300	600
GPS35	1360	763	2970	3160	900	1800

EXPLANATION

Files of predictions for each satellite chosen were kindly provided by Chris Moore. They were generated in the "Inertial" reference frame (True-of-date) at 1-second intervals, as geocentric Cartesian X,Y,Z coordinates They are labeled "I"

The "I" coordinates were then transformed to body-fixed Greenwich coordinates, labeled "G", by rotating through Greenwich Mean Sidereal Time. These coordinates are those proposed for the ILRS Consolidated Prediction Format (CPF). In this study, UT1-UTC and polar motion were ignored.

The "G" coordinates were then transformed to the relative topocentric Cartesian coordinates (East, North, Up) at the Mount Stromlo SLR station, labeled "T", by rotating through longitude and latitude.

Finally, the "T" coordinates were transformed to Range, Azimuth and Elevation, labeled "P" (for Polar), by the usual formulae.

These four data sets were considered to be "truth". They each covered about a day of predictions.

Interpolation errors were examined for a variety of circumstances:

•Grid spacings of 15, 30, 60, 120, 240, 480 or 960 seconds, with tabular points ("nodes") selected from the "true" data;

•Interpolation orders 4, 6, 8, 10, 12 (degrees one less than these);

•Interpolating into the I, G, T or P reference frames, at every second. When interpolating using tabular points in the first three systems, the interpolation results were transformed to range, azimuth and elevation .

Each circumstance was characterized by its "RSS", i.e. the square root of the average square of the deviates "interpolated - truth", over all the 1-second points. The various RSSs were plotted on log-log graphs against grid spacing; and the grid spacings for the nominated values of RSS, shown in Table 1, were then obtained by inverse logarithmic interpolation. The relevant graphs for LAGEOS are shown in Figures 1 and 2.
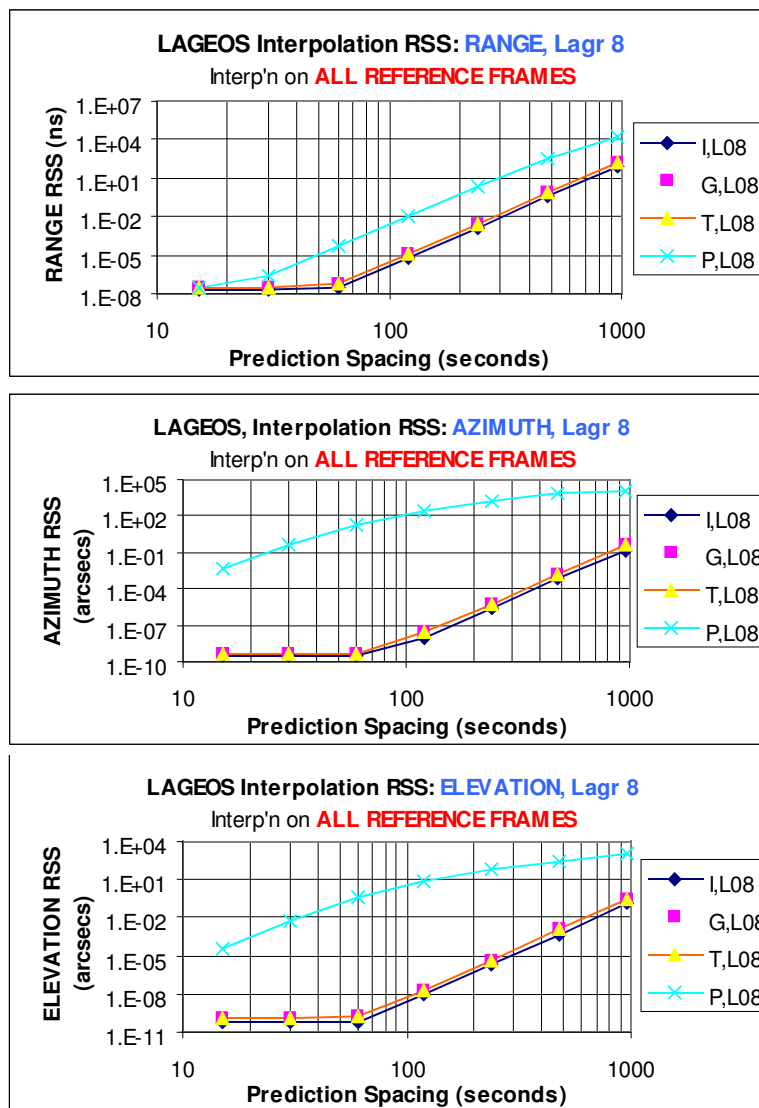
OUTCOMES

Figure 1: Log-log graphs of Range, Azimuth and Elevation Interpolation Errors using an 8th-order
interpolator in Inertial XYZ (I), Greenwich XYZ (G), Topocentric ENU (T) and local Az/El/R
(P) systems.

From Figure 1 it is seen that the results are virtually identical when interpolating with an 8th-order
interpolator on any of the Cartesian systems (I,G,T), but much worse when interpolating directly in range,
azimuth and elevation (P). This general result holds for all satellites tested and for all interpolator orders
used, although their graphs
are not shown here.

Both sets of figures also show that, after a "floor" due to subtraction of nearly equal large numbers, the log-
log relationships are linear, consistent with the theoretical behaviour of interpolation errors. This, too, is a
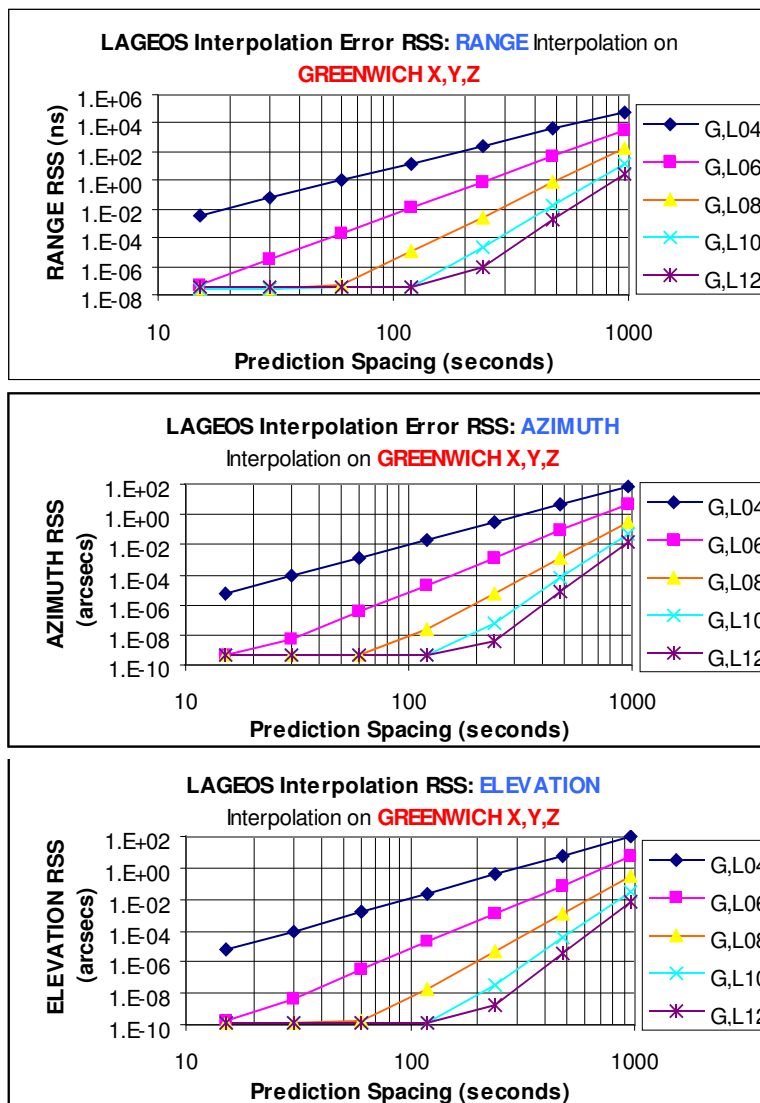general result.

Figure 2: Log-log graphs of Range, Azimuth and Elevation Interpolation Errors using interpolators of order 4, 6, 8, 10 and 12 in the Greenwich XYZ (G) system. .

CONCLUSIONS

From the point of view of interpolation error, the grid spacings proposed for the ILRS Consolidated Prediction Format are adequate for producing better than 1 ns accuracy in range, and 1 arcsec accuracy in azimuth and elevation, provided that an 8th-order interpolator (or higher) is used on Cartesian coordinates. They are not adequate for producing ranges with 10 ps accuracy (if anybody would ever want such accuracy in predictions).

They are grossly inadequate for interpolating directly into tables of range, azimuth and elevation!

CAUTIONS

Transforming from an inertial (or quasi-inertial) reference frame to the Greenwich (body-fixed) frame involves application of sidereal time, which in turn requires the Julian Date (JD). Now, a typical satellite range rate is 5 km/sec, or 1 ns (2-way) per 30 μs. If the formula for GMST given, for example, on page B6 of "*The Astronomical Almanac 2005*" is followed blindly at an arbitrary time, then about 17 decimal places are required for the JD to reach the 30 μs resolution needed. My Windows-based 32-bit computer only gives about 14 decimal places in Fortran double precision, so the rounding error is highly significant - it caused a 30 ns saw-tooth during my experiments. A simple remedy is to calculate GMST for exactly 0h UTC on the required day, reduce it modulo 86400^s, then add [UTC + (UT1-UTC)] multiplied by the sidereal conversion factor 1.00273781191135448 ("*IERS Conventions (2003)*", p.38). Or simply increase the precision of calculations…..

[*Confession*: I have always known about this, but forgot. The reminder came when the interpolation errors on "G" were much larger than on "I", which was hard to understand since the transformation between them is essentially extremely smooth. There's no fool like an old fool.]

It was also humbling to have to take several goes at getting the azimuths strictly continuous before their interpolations, because the ATAN2 function only returns values in the range $-p < Az \ddot{i} \ p$. Failures showed up as ridiculously large interpolation RSSs, e.g. 10^5 seconds of arc. [The old fool does still remember to do simple, yet comprehensive, sanity checks on all his software….]