Consolidated Laser Ranging Prediction Format
Version 2.00

for the ILRS Prediction Format Study Group
of the ILRS Data Format and Procedures Working Group
SIGNIFICANT CHANGES HIGHLIGHTED IN YELLOW

28 February 2018

Revision History
0.2 1.10 – 10 January 2018

- Clarified documentation on certain fields.
- Added epoch of the transponder oscillator drift to "H4" record.
- Expanded sub-daily sequence number from 1-9 to 1-99 on file name and in "H1" header record.
- Split Target ID into Target reflector type and Target location.
- Updated leap-second handling.
- Clarified time in file name and pass start time in "H2" header record.
- Rewrote manual to remove most references to TIV/IRV format.
- For more detail, see Appendix G.

Introduction
In 2006, due to requirements for more accurate predictions and a need to provide predictions for different target types, the existing Tuned Inter-range Vector (TIV) and lunar formats were replaced by the Consolidated Prediction Format (CPF), which was flexible enough to handle earth satellites, lunar retro-reflector arrays, lunar satellites, and various transponders. Transponders were being developed for the first time, and would have needed yet another prediction format, if it were not for the CPFs. In addition, time biases and other corrections could be built into the predictions without requiring separate files. Instead of using an integrator to handle a single state vector per day, the CPF files with many records per day are interpolated with a high order (9th) polynomial.

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 arc-seconds for Mars and asteroids, and possibly more for any close-in spacecraft in transit.

The orbits of the moon and other major solar system objects are computed in the solar system barycentric reference frame, so they cannot be integrated easily on site in the way artificial Earth satellites can. However, one can readily interpolate tables of geocentric coordinates for these objects and 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 includes x, y, z and a corresponding time for each ephemeris entry. This and other specialized information are spread over several records for a day, the number and type depend on the altitude and the target class. The time between adjacent entries will normally be constant and will be small enough to meet any reasonable precision requirements using the supplied interpolation software. The time is 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 position10, directions 1 and 2, and corrections 30, directions 1 and 2 should be treated as a single-time set of predictions. 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 words, the records are not in strict time order. See the transponder example in Appendix B or the records below.

```
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
```

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

4. **Line-length limits and method of transmission**
There are no length limits (within reason). 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 shows the width and the significant digits for each field. **The width and the format represent typical width for planning purposes. Change as needed.**

6. **True body fixed system of date and Earth rotation parameters**
   The coordinate system used in the CPF 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, Earth's pole positions have been included in the predicted positions. Since fresh Earth orientation parameters (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, or to back out values that may have been used in the predictions. 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**
   The CPF prediction file for a particular satellite contains several days worth of data. Seven days of predictions is standard, though some providers' predictions may be shorter. Multi-day files help the stations interpolate over day boundaries, which could otherwise cause problems. Multi-day files also allow ranging in case something prevents daily CPF downloads. Header records appear only once per file.

8. **Integration past end of file**
   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 cannot be handled in this way.)

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

   Maneuvers can be built into the CPF files. In these cases, maneuver messages are only needed to warn stations of the event. It has turned out that it is often not possible to accurately predict the trans- and post-maneuver satellite positions. In these cases the maneuver messages are still valuable, as are special post maneuver CPFs.

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

11. File naming conventions

The following file naming convention is required for the new prediction format:

target_cpf_yymmdd_nnnvv.src

where the fields are as follows:

- target:
  - the official satellite name (See table in Appendix C and the up-to-date list at https://ilrs.cddis.eosdis.nasa.gov/missions/satellite_names.html.)
  - no special characters ("-", "_", "#", etc) or spaces are allowed
  - variable length with a maximum length of 10 characters
- yymmdd:
  - start year, month, and day of the CPF from the CPF H2 record
- nnn:
  - ephemeris version number. This is the day of year from the production date in the CPF H1 record. (Originally, 500 was added to distinguish CPFs from TIVs in time bias and other messages.) This field is three digits in length with zero leading fill.
- vv:
  - version number within the day. This is two digits with zero leading fill, starting with '01', and increasing to '99'.
- src:
  - prediction provider code, 3 characters long.

Format Field Comments

1. Target IDs and Names

SIC (Satellite ID Code), COSPAR (aka ILRS ID), and NORAD IDs (aka Satellite Catalog Number) and satellite/target name are included in the prediction headers as a convenient cross reference.

- Satellite/target names should be taken from the standard list at https://ilrs.cddis.eosdis.nasa.gov/missions/satellite_names.htm.
- The SIC is assigned by the ILRS for laser tracking targets.
- The ILRS ID can be derived from the official COSPAR number, as detailed on the ILRS web site and below.

COSPAR ID to ILRS Satellite Identification Algorithm
COSPAR ID Format: (YYYY-XXXA)
YYYY is the four digit year of when the launch vehicle was put in orbit *XXX is the sequential launch vehicle number for that year* *A is the alpha numeric sequence number within a launch* *Example: LAGEOS-1 COSPAR ID is* **1976-039A** *Explanation: LAGEOS-1 launch vehicle was placed in orbit in 1976; was the 39th launch in that year; and LAGEOS-1 was the first object injected into orbit from this launch.*

ILRS Satellite Identification Format: (YYXXXAA), based on the COSPAR ID

YY is the two digit year of when the launch vehicle was put in orbit
XXX is the sequential launch vehicle number for that year
AA is the numeric sequence number within a launch
Example: LAGEOS-1's ILRS Satellite ID is **7603901**

2. **Start dates and times**
The relationships among the date/time of the first "10" position record, the start time on the H2 Basic Information header and the date on the CPF file name have been the source of some confusion. To clarify, the start date and time should refer to the intended date and time for the CPF's use. In other words,
   a) There may be 4-6 "10" records dated prior to the intended start date and time (e.g., 0 hours UTC) of the CPF. This allows the interpolation at the date and time of the intended start time (e.g., 2018 6 1 0 0 0) to have full precision.
   b) Put the date from 2) (2018 6 1 0 0 0) into the H2 record start date/time, ignoring the fact that the first '10' records are earlier than this time.
   c) Set the date on the CPF file name to 180601.
   d) If the the first "10" record is at 0 hours UTC or a little before or after, the H2 start date should also be 2018 6 1 0 0 0 and the CPF file name data should also be 180601.

3. **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 present, the stations can correct the interpolated two-way range from the center of mass to the reflectors by subtracting twice this correction.

   Position vectors of non-spherical, attitude-controlled satellites can be given for either 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 the GNSS satellites (GPS, GLONASS, Galileo, COMPASS) are seen from the Earth's surface within a small angle only, reflector corrections can be given as an approximate radial correction in header record H5 if the given positions are referred to the center of mass.

4. **Estimated accuracy**
These optional records give an estimate of the expected accuracy (peak-to-peak) at certain points during the day. The estimates 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. They will be especially valuable to automated stations so that

excessive time is not spent in searching for an optimal range gate and tracking settings.

5. **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 apply the time argument to the interpolator appropriately.

   Prediction files can 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'.

   As of the leap second on December 31, 2016, the ILRS has adopted the "coffee break" technique to deal with the leap second discontinuity. A crew ranges with the CPFs without the leap second until near the time of the leap second. They can then "take a coffee break" until some time after the leap second has passed. Then the crew uses the next day's CPFs which include the leap second. The leap second flag is ignored.

6. **Position and velocity fields**
   For artificial Earth satellites, these fields do not include light time iteration corrections. These 10-0 (record type 10, direction flag = 0) records contain 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-421), the 10-1 and 10-2 records are used and are the result of light time iteration. For this case, the vector spans fire time at the geocenter to bounce time at the target (record 10-1) and from bounce time to return time at the geocenter (record 10-2).

   The corresponding elements in the outgoing and incoming position fields will have opposite signs. The same is true for the velocities.

7. **Correction fields**
   As noted above, several complications arise in predicting ranges and pointing angles for solar system targets. They are essentially relativity and aberration. The aberration can be broken into light-time aberration, which applies to all targets (including earth satellites), and stellar aberration, which applies to those targets (such as the moon and

planets) computed from solar system ephemerides. Near-Earth artificial satellites are usually computed in the geocentric reference system and do not require the so-called stellar aberration.

Light time aberration is already applied implicitly in the state vectors, so it affects both range and pointing angles. Stellar aberration corrections (for the moon and other solar system bodies) are applied in computing the topocentric pointing angles. The relativistic corrections are computed separately and applied to the ranges. See Seidelmann, 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 into an elapsed time, which can be observed at a station. This correction can be 200 m for a round trip range to Mars and is necessary because the position 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 Seidelmann.

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 the outgoing ones. For pointing 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. They 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.

8. 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. These objects are given bogus IDs, perhaps negative numbers. A list of targets, names, and IDs will be supplied as needed by the prediction provider.

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 pointing angles to any arbitrary lunar surface feature whose selenocentric coordinates they supply. Stations without arc-second level pointing accuracy may need this as a basis for offset pointing to the reflectors. Ranges computed in this way are not ("will not be" or "are not"?) 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 the 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 (GAST). A libration vector is then created from the rotation vector of (ϕ,θ,ψ) (X X Newhall, private correspondence; see sample code) and pre-multiplied by the station coordinate vector (X, Y, Z) (change to (X, Y, Z) to be consistent with those in later text and appendixes ?). The result is added to the rotated, aberrated coordinates. The resulting vector is in the inertial coordinates of the lunar feature. This vector is then rotated back through the GAST to give the body fixed coordinates of date for pointing to the lunar feature. These coordinates can then be converted to RA/Dec, then to HA/Dec, and, finally, to azimuth/elevation. If the lunar positions and velocities are supplied in inertial coordinates (reference frame = 1), the first rotation, through -GAST, is unneeded.

9. Transponder fields

Transponders can be either synchronous or asynchronous. Synchronous transponders fire when a laser pulse is 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 the ground station record transmit and receive time based on their own 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) - $1x10^{-5}$ to $1x10^{6}$ Hz
  - Asynchronous transponders only.
- Transponder transmit delay – 1 msec to 10 sec
  - 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
  - Transponder clock reference time of oscillator drift is provided in seconds
- Relativity Correction to Satellite Oscillator Time Scale for One-Way Range Rates -- 1 cm/sec to 1.5 m/sec (0.03 nsec/sec to 5 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 pointing angles and range based on the rotation angles of a planet or the 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 Seidelmann 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).

The experience with the only lunar transponder so far, LRO-LR, is that the prediction provider distributed CPFs with records at 15-second intervals for the LRO spacecraft. The extreme precision required for ranging to reflectors is not needed for transponders.

Interpolator Definition
The baseline for interpolation of the CPF predictions is a 10-point (9^{th} order) Lagrange interpolation algorithm, which allows for records with variable time spacing. A sample interpolator was written to accompany the format. The following record spacings are reasonable, using position (X, Y, and Z) only. Note that the MGS (Mars Global Surveyor) interval is 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 (8 point)	Degree 9 (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	N/A	0.3

Ranging stations can use one of a variety of interpolation schemes, preferably Lagrange (Splines are strongly discouraged). However, the baseline scheme is use of the 10-point Lagrange interpolation with a maximum error of less than 1 nsec in range, which is due to production and interpolation of the predicted ephemeris. 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 the Cartesian (X, Y, Z) space and not in the range/pointing angles for acceptable accuracy (see Appendix E). 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 interpolator is available on the ILRS web site (https://ilrs.cddis.eosdis.nasa.gov/data_and_products/formats/cpf.html) 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 (the moon, planets, or satellites of either) must be handled differently, but the software package will call the routines which are necessary based on the target. See Appendix D for more details.

Constants

The speed of light used by both prediction centers and stations should be the IERS Convention 2003 standard of 299792458 m/sec. Site coordinates should be in the International Terrestrial Reference Frame (ITRF). Although JPL's DE-403 and DE-421 ephemerides are 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 the CPF format for improved prediction accuracy and inclusion of exotic targets have been met. This format covers four different target types in one prediction format and sample software set. It opens up opportunities for most stations to range to a wider variety of targets and naturally overcomes several difficulties in previous tracking prediction formats. The format comes at the expense of larger file transfers. It does, however, provide a flexible platform for laser ranging predictions into the foreseeable future.

References

Abramowitz, M. And Stegun, I. A., Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables, National Bureau of Standards, Washington, 1964, p. 878.

Davies, M. E., et al (1991) "Report of the IAU/IAG/COSPAR Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites: 1991," Celestial Mechanics, 53, 377-397.

Seidelmann, P.K., ed. Explanatory Supplement to the Astronomical Almanac, University Science Books, Mill Valley, 1992.

Appendix A. Prediction Format Version 2.00

1) Data headers

NOTE: ALL fields MUST be separated by spaces, since these records are read as free format. The field-widths (e.g., I5, f12.5) are suggestions, and should be sized according to the target's needs. The field specifiers are based on FORTRAN. Samples of the C equivalents are A3 → %3s; I2 → %2d; F12.5 → %12.5f.

Header type 1 Basic information - 1 (required)

1-2	A2	Record Type (= "H1")
	A3	"CPF"
	I2	Format Version = **2**
	A3	Ephemeris Source (e.g., "HON", "UTX ")
	I4	Year of ephemeris production
	I2	Month of ephemeris production
	I2	Day of ephemeris production
	I2	Hour of ephemeris production (UTC)
	I3	Ephemeris Sequence number
	I2	Sub-daily Ephemeris Sequence number
	A10	Target name from official ILRS list (e.g. lageos1)
	A10	Notes (e.g., "041202","DE-403") with no spaces

Header type 2 Basic information - 2 (required)

1-2	A2	Record Type (= "H2")
	I8	ILRS Satellite ID (Based on COSPAR ID)
	I4	SIC (Provided by ILRS; set to “-1” for targets without SIC)
	I8	NORAD ID (i.e., Satellite Catalog Number)
	I4	Starting Year
	I2	Starting Month
	I2	Staring Day
	I2	Starting Hour (UTC)
	I2	Starting Minute (UTC)
	I2	Starting Second (UTC)
	I4	Ending Year
	I2	Ending Month
	I2	Ending Day
	I2	Ending Hour (UTC)
	I2	Ending Minute (UTC)
	I2	Ending Second (UTC)
	I5	Time between table entries (UTC seconds)(=0 if variable)
	I1	Compatibility with TIVs = 1 (=> integrable, geocentric ephemeris)
	I1	Target class 0=no retroreflector (includes debris)

1=passive retroreflector
2=(deprecated – do not use)
3=synchronous transponder
4=asynchronous transponder
5=other

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)
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)
I1 Center of mass correction
0=None applied. Prediction is for center of mass of target
1=Applied. Prediction is for retro-reflector array
I2 Target location/dynamics
0=other
1=Earth orbit
2=lunar orbit
3=lunar surface
4=Mars orbit
5=Mars surface
6=Venus orbit
7=Mercury orbit
8=asteroid orbit
9=asteroid surface
10=solar orbit/transfer orbit (includes fly-by)

Header type 3 Expected accuracy

1-2	A2	Record Type (="H3")
	I5	Along-track run-off after 0 hours (meters)
	I5	Cross-track run-off after 0 hours (meters)
	I5	Radial run-off after 0 hours (meters)
	I5	Along-track run-off after 6 hours (meters)
	I5	Cross-track run-off after 6 hours (meters)
	I5	Radial run-off after 6 hours (meters)
	I5	Along-track run-off after 24 hours (meters)
	I5	Cross-track run-off after 24 hours (meters)
	I5	Radial run-off after 24 hours (meters)

Header type 4 Transponder information

1-2	A2	Record Type (= "H4")
	F12.5	Pulse Repetition Frequency (PRF) in Hz

F10.4 Transponder transmit delay in microseconds
F11.2 Transponder UTC offset in microseconds
F11.2 Transponder Oscillator Drift in parts in 10^{15}
F20.12 Transponder Clock Reference Time (seconds, scaled or unscaled)

Header type 5 Spherical satellite center of mass correction

1-2	A2	Record Type (= "H5")
	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 as free format. The field-widths (e.g., I5, f12.5) are suggestions, and should be sized according to the target's needs. The field specifiers are based on FORTRAN. Samples of the C equivalents are A3 → %3s; I2 → %2d; F12.5 → %12.5f.

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")
	I1	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 reference frame,
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 in the corresponding old TIV format.
- 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 to that of the transmit vector.)

Appendix B - Sample Prediction Configurations

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

1. Earth-orbiting artificial satellites
A typical record configuration for most satellite is as follows:

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

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

Example:
```
H1 CPF 2 AIU 2005 11 16 4 320 1 gps35
H2 9305401 3535 22779 2005 11 15 23 59 47 2005 11 20 23 29 47 900 1 1 0 0 0 1
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 is 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 2 UTX 2005 11 16 14 320 1 apollo15 jpl_de-403
H2 103 103 0 2005 11 17 0 0 0 2005 11 21 23 45 0 900 0 1 0 0 0 3
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 2 UTX 2005 11 16 14 320 1 luncenter jpl_de-403
H2 99 99 0 2005 11 17 0 0 0 2005 11 21 23 45 0 900 0 1 0 1 0 3
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
```

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 is 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 2 GSC 2004 03 30 12 90 1 lro
H2 99999999 9999 99999999 2004 04 04 00 00 00 2004 04 04 05 00 00 10 0 4  0 0 0 2
H3 0 0 0 1 0 0 5 1 1
H4 1999.91715 273.1500 2004.93 15.30 478579238.40
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 is:

> 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 2 GSC 2004 03 30 12 90 1 xponder1
H2 99999999 9999 99999999 2004 04 04 00 00 00 2004 04 04 05 00 00 10 0 3 0 0 0 2
H3 0 0 0 1 0 0 5 1 1
H4 0.00000 273.1500 0.00 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

The CPF format provides better prediction accuracy than the previous TIV format for artificial satellites, especially the low Earth orbit (LEO) satellites, as well as a common system that includes 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 the philosophy and format details, which can be found at the addresses listed in the **Resources** section.

Satellite Laser Ranging (SLR) Predictions (Earth orbiting satellites)

1) CPF predictions are tabulated satellite state vectors generally in the geocentric Earth-fixed coordinate system of date known as the 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, although some providers supply files with as little as three-days of data. The prediction center should re-issue prediction files for low satellites several times per day, if necessary.

4) When interpolated with a 10-point Lagrange interpolator, the CPF file must reproduce 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 in all fields of the records that are written. All 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 transponders only, and header 5 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 the 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, the 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 at 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 hour 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'.

Note: the leap second flag is currently ignored. Leave it set to '0'. See item 4 in the Format Field Comments above.

9) CPF files should be named in accordance with the following format:
satellite_cpf_yymmdd_nnnvv.src
where:
- satellite:
  - the official satellite name (See table below and the up-to-date list at https://ilrs.cddis.eosdis.nasa.gov/missions/satellite_names.html.)
  - no special characters ("-", "_", "#", etc.) or spaces are allowed
  - variable length, with a maximum length of 10 characters
- yymmdd:
  - Start year, month, and day from the H2 record
- nnn:
  - ephemeris version number. Ephemeris production day of year from the H1 record. This field is three digits with zero leading fill.
- vv:
  - version within the day. Two digits with zero leading fill, starting with '01'.
- 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) Maneuver 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 can 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

Follow the same procedures as for “SLR Predictions” with the following differences.

1) 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 vector spans from the target at bounce time to the geocenter at return time.

2) 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.

3) 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.

4) 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 out-bound/in-bound leg pair, the relativistic correction must be one-way, as it will be added twice.

5) 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 (not up-to-date):

adeos
adeos2
ajisai
beaconc
champ
diadem1c
diadem1d
envisat
ers1
ers2
etalon1
etalon2
fizeau
geos3
gfo1
gfz1
glonass## (where ## is the 2-digit GLONASS satellite number)
gpb
gps35
gps36
gracea
graceb
icesat
jason1
lageos1
lageos2
larets
lre
meteor3
meteor3m msti
reflector
resurs
starlette
starshine2
starshine3
stella
sunsat
tips
topex
westpac
zeia

LLR Targets:

apollo11
apollo14
apollo15
luna17
luna21
luncenter

An up-to-date list will be maintained at:
https://ilrs.cddis.eosdis.nasa.gov/missions/satellite_names.html

2. Full documentation
https://ilrs.cddis.eosdis.nasa.gov/data_and_products/predictions/index.html

3. Sample Software
Enter https://ilrs.cddis.eosdis.nasa.gov/data_and_products/formats/cpf.html to download the software “tar” file.

4. EDC and CDDIS upload instructions
Contact Carey Noll at carey.noll@nasa.gov or
Christian Schwatke at Christian.Schwatke@tum.de .

5. For reference, CPF files can be found at:
ftp://cddis.gsfc.nasa.gov/pub/slr/cpf_predicts or
ftp://edc.dgfi.tum.de/pub/slr/cpf_predicts/.
or contact Carey Noll (carey.noll@nasa.gov) to be added to the email exploder.

6. CPF email exploder:
Contact Christian Schwatke at Christian.Schwatke@tum.de or check the ILRS web page (https://ilrs.cddis.eosdis.nasa.gov/about/contact_ilrs/ilrspred.html).

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 were 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 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 the 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 to 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 pointing 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 be between the 5^{th} and 6^{th} points for the 10-point interpolation, or precision will be degraded.

4) Due to rule 3), the interpolator needs 5 extra records at the beginning and the 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 hour 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

https://ilrs.cddis.eosdis.nasa.gov/data_and_products/formats/cpf.html

2. Sample Software

The software is organized into the following directories:

    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. Directories with names ending in "_c" contain C code, directories with names ending in "_cpp" contain C++ code, and directories with names ending in "_f" contain FORTRAN.

common_c, common_f -
: Routines that read and interpolate a CPF file are included. Also, the directory 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 pointing angles for SLR predictions. Test input and output files are included.

cpf_llr_c, cpf_llr_f -
: Programs in these directories produce range and pointing 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 pointing angles for SLR, LLR and transponders. Test input and output files

are included. This code 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 prediction centers and their test stations. It can be installed in any station with a feeling of paranoia.

cpf_conv_c

This contains the program cpf_conv which automatically converts the input CPF file to the other version. If the input CPF is version 1, it will be converted to version 2. If the input CPF is version 2, it will be converted to version 1.

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 https://ilrs.cddis.eosdis.nasa.gov/data_and_products/formats/cpf.html and select "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://edc.dgfi.tum.de/pub/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
https://ilrs.cddis.eosdis.nasa.gov/data_and_products/predictions/prediction_centers.html
Use backup providers when usable predictions are not available from the primary providers.

Appendix E: Common Abbreviations

CRD	Consolidated laser Ranging Data Format
COSPAR	Committee on Space Research, a Committee of ICSU, the International Council for Science.
CPF	Consolidated laser ranging Prediction Format
FWHM	Full width at Half Maximum, relating to pulse width
ILRS	International Laser Ranging Service
LLR	Lunar Laser Ranging
LRO	Lunar Reconnaissance Orbiter
ND	Neutral Density, which describes opacity of a broad band optical filter.
NORAD	The North American Aerospace Defense Command
ns	nanoseconds
ps	picoseconds
RMS	Root Mean Square. Same as standard deviation.
SLR	Satellite Laser Ranging
SCH	Station Change Indicator
SCI	Station Configuration Indicator
SIC	Satellite Identification Code, a 4 digit satellite descriptor.
SRP	System Reference Point, usually described as the first non-moving point in the telescope light path.
µs	microseconds
UTC	Coordinated Universal Time, formerly known as Greenwich Mean Time (GMT).
XML	eXtensible Markup Language.

Appendix F – Maximum Predictions Grid Spacings

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 as “I”.

The “I” coordinates were then transformed to body-fixed Greenwich coordinates, labeled as “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 as “T”, by rotating through longitude and latitude.

Finally, the “T” coordinates were transformed to Range, Azimuth and Elevation, labeled as “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 of 4, 6, 8, 10, 12 (degrees are 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

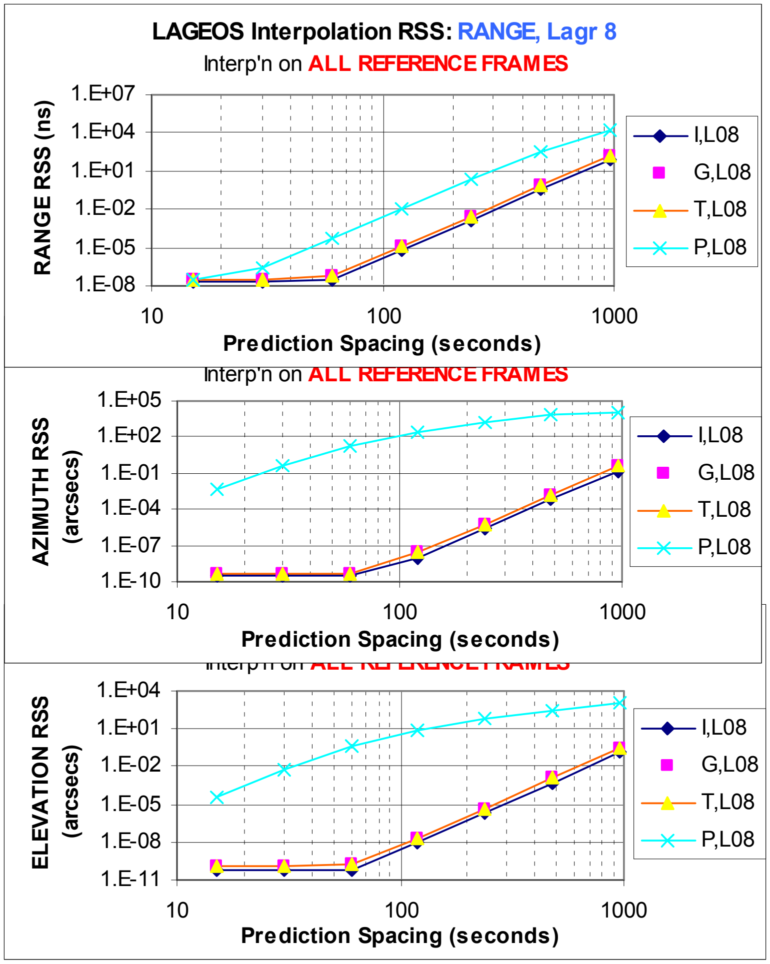
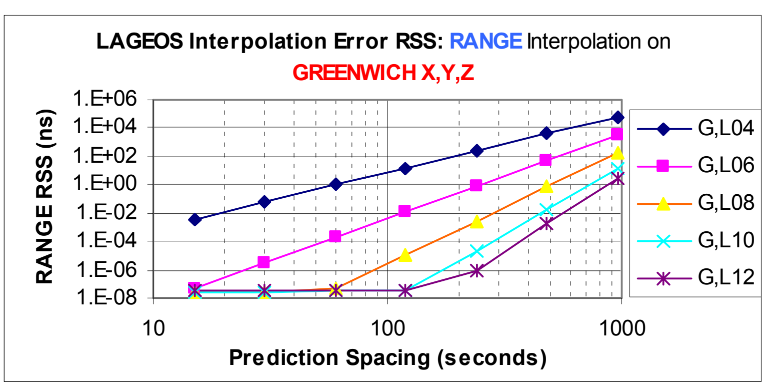


Figure 1: Log-log graphs of Range, Azimuth and Elevation Interpolation Errors using an 8th-order interpolator in Inertial XYZ (I), Greenwich XYZ (G), Topocentric ENU (T) and local Az/El/R (P) systems.

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.



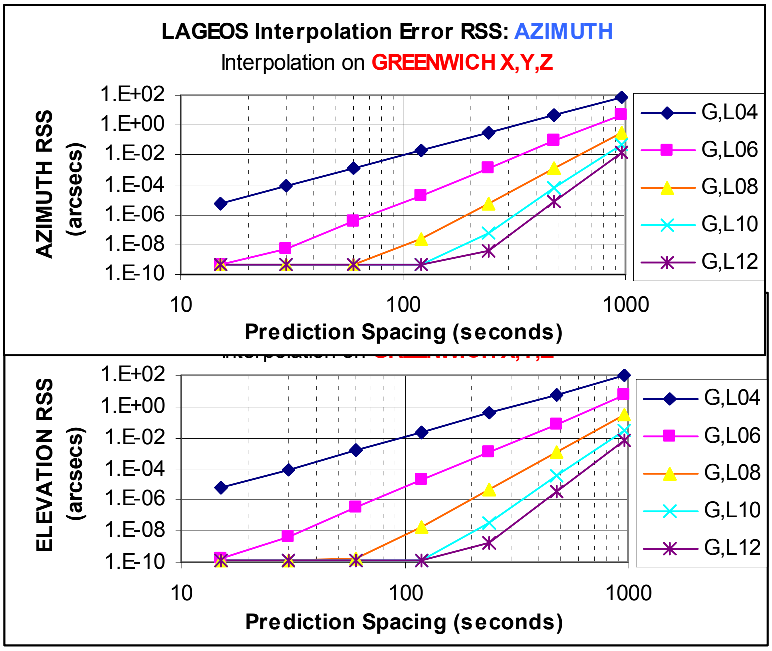


Figure 2: Log-log graphs of Range, Azimuth and Elevation Interpolation Errors using interpolators of order 4, 6, 8, 10 and 12 in the Greenwich XYZ (G) system.

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, 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 by modulo 86400, then add [UTC + (UT1-UTC)] multiplied by the sidereal conversion factor 1.002737811911354448 ("*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 $-\pi < Az < \pi$. 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…..]

Appendix G: Changes from CRF v. 1 to CRF v. 2

CRD and CPF Format and Manual Updates

28 February 2018

Both the CPF and CRD formats have become a flexible way to distribute laser ranging predictions and data, respectively. Now that there have been years of experience with these formats, it is clear that there are some improvements that would make them more complete for several types of users.

1. **In general**
    1. Both formats will now be at version 2.
    2. Sample code changes will allow the reading of both version 1 and 2 CPF and CRD files.
    3. Manuals and included web links have been updated.

2. **CPF changes**
    1. The European Laser Transfer (ELT) mission required a change to the "H4" header record to include the epoch of the transponder oscillator drift.
    2. Due to the large drag effects on the International Space Stations (ISS), the ELT mission also required the ability to distribute more than 10 CPF versions each day. To accommodate this change, the sub-daily part of the sequence number will now be 2 digits long, with values from 1-99, with zero-fill.
    3. Target type in header H2 has been split into the following two fields to clarify functionality.
        1. "Target class" describes the reflector hardware: none, passive, synchronous transponder, or asynchronous transponder.
        2. "Dynamics/location" describes the location of the reflector: in orbit, on a surface, and the body (earth orbit, lunar orbit, lunar surface, etc.), other, or unknown.
    4. Stations are encouraged to build in the capability to handle CPFs written in the inertial reference frame ("H2" record, Reference frame = 2). While CPFs have so far only been allowed to be released in the body-fixed frame of reference, the ILRS would benefit from having this capability.
    5. The manual has been rewritten, eliminating dated information on conversion from IRV to CPF files and from older data formats to CRD. Other areas have been updated as needed.
    6. Proposed lunar/planetary one-way relativity correction records to use with transponders are not being added this time, and will be considered in the future only if there is a demonstrated need.
    7. NOTE: Read and observe the new method of handling leap seconds instituted in 2016, in which there is no tracking through the leap second.
    8. NOTE: Various prediction centers handle start time and length of CPF files differently. Some start on the even day. Some start 5 records early, so that the full accuracy of the 10-point interpolation will be available at the start of the day.

Also, although the standard length of a CPF file is 5 days, certain providers have chosen to make their files longer or shorter.

9. The time on the CPF file name is now defined as being the same as the start time on the H2 record; the date/time on the H2 record should now be the intended start date of the CPF, allowing predictions with several records before the start of a new day to use the date of the new day on the H2 record; and the sequence number is now defined as being the day of year corresponding to the ephemeris production date on the H1 record, without adding 500 (and the sub-daily sequence number takes two digits on the filename).

3. CRD changes

1. NOTE: The Station Epoch Time Scale (“H2”) must be set to 3 (UTC USNO), 4 (UTC GPS), or 7 (UTC BIH). Stations MUST NOT use any other values without agreement from the Analysis Standing Committee.
2. Target type in header H2 has been split into two fields to allow for clearer functionality.
    1. “Target class” describes the reflector hardware: none, passive, synchronous transponder, asynchronous transponder.
    2. “Location/Dynamics” describes the location of the reflector: in orbit, on a surface, and the body (earth orbit, lunar orbit, lunar surface, etc.).
3. The CRD Seconds of Day field in any of the data record types is still not allowed to exceed 86400. A problem that seemed to require extending the upper bound beyond 86400 has been solved in another way.
4. Operations Centers' (OCs') range of acceptable values for each field will be included in an appendix. (For now this will only include fields from CPF version 1.)
5. Shot records (“10”) now include the fire energy; the return energy is already recorded.
    1. These fields are still in arbitrary units and are unlikely to be meaningful for comparison between stations. These fields are not in normal point (“11”) records.
6. The normal point record (“11”) has been keeping the return rate for SLR and the S:N for LLR in the same field. They are now in separate fields: Return Rate, and Signal to Noise Ratio.
7. APOLLO lunar ranging station LLR processing version and other processing details will continue to be recorded in comment records (“00”), not in new lunar-specific records.
8. CRD software versions are now included in the new “C5” software configuration record.
    1. Capturing software versions can help analysts and stations isolate data anomalies created by software changes.
    2. The record(s) include ranging, calibration, filtering, normal pointing and related software that are in the data path. In other words, this is software which could alter the quality of the data if an incorrect modification were made.
9. Models and serial numbers of meteorological equipment used in the current pass are recorded in the new “C6” configuration record.

1. Equipment listed are those which measure pressure, temperature, humidity. Another piece of meteorological equipment can be included as well. This record should correspond to the meteorological equipment listed in the ILRS Site Log.

10. More meteorological data can be added to the Meteorological Supplement Record (“21”).
    1. Sky temperature.
    2. The “precipitation” field has been renamed “weather conditions”. Previous character strings (e.g. “fog”) will continue to be accepted as well as the 2-digit SYNOP/WMO present weather code.
11. NOTE: The “Epoch delay correction” in the “Timing System Configuration Record” (“C3”) is essentially the same as the “Estimated Station UTC Offset” in the “Transponder (Clock) Configuration Record” (“C4”), but their units are different due to different applications – microseconds vs. nanoseconds. When the “C4” record is present, its value supersedes the value in the “C3” record.
12. The Compatibility record (“70”) is obsolete and should no longer be sent.
13. The Prediction Record (H5) has been added to log the CPF or TLE filename used in tracking.

A2	Record Type (= "H5” or “h5”)
I2	Prediction type 0 = Other 1 = CPF 2 = TLE
I2	CPF or TLE year of century
A6/A12	CPF date and hour (MMDDHH) from “H1” record; or TLE epoch day/fractional day from line 1
A3	Prediction provider from CPF H1; TLE does not include this field, but it should be available at the station.
I5	CPF Ephemeris sequence and sub-daily sequence numbers from H1; or TLE Revolution number from line 2

14. Debris and other non-ILRS tracking uses
    1. H2: There are now alternate names for Crustal Dynamics Project (CDP) pad ID, system number, and move number for non-ILRS tracking stations, e.g., System/Sensor identifier, System/Sensor number, and Sequence number.
    2. H2: The tracking network name (A10) is added to the end of the record for network data exchange. For SLR, this field contains the network, such as “NASA”, “WPLTN”, etc. For debris tracking, this is the debris tracking network, etc.
    3. H3: “no reflector” has been added to the list of possible target types.
    4. 12, 30: Azimuth, elevation, and range rates have been included in appropriate records.
    5. Filename conventions (debris and other non-ILRS tracking ONLY, not to go through OCs) include the network name to uniquely identify a station, e.g.,

       “networkname_ssss_satname_crd_yyyymmdd_hh_rr.xxx,

       where the networkname represents a debris or other network, the names of which are not yet defined.

4. CPF and CRD

1. Added “Satellite Catalog Number” to NORAD ID field name, since they are interchangeable.
2. Made the header records free format. The configuration and data records already are free format.
    1. This is definitely not backward-compatible, though the software modifications should be minor.
    2. CPF note field will include up to 10 non-spaces following the target name.
3. There have been cases where the COSPAR ID to ILRS ID conversion did not follow the documented conversion scheme. This has only happened for two satellites so far and will be dealt with on a case-by-case basis. A general fix would probably require a change from 7 to 8 digits in the ILRS ID, which is not justified at this time.

5. Implementation plans

CPF update implementation plans:

1. What needs to be changed?
    1. The manual.
    2. Sample code: Needs backward compatibility for reading both version 1 and 2.
    3. Prediction Providers: At the beginning, version 2 CPFs will be provided by the ELT mission and a few others.
    4. OCs and DCs must provide space and handling for the V2 CPFs.
    5. Station software: Ingest new format at the stations, especially those intending to track ELT.
2. Milestones and associated dates will be provided in other communications.

CRD update implementation plans:

1. What needs to be changed?
    1. The manual.
    2. Sample code: Needs backward compatibility for reading both version 1 and 2.
    3. OC software: Validation code must handle new fields.
    4. OCs and DCs must provide space and handling for the V2 CRDs.
    5. Analysis software: Analysis Standing Committee needs to address the changes and ensure that the users can read both formats.
    6. Station software: Mainly processing and normal point code.
    7. OCs, Data Centers, analysts, and debris tracking SC must accept original and new versions.
2. Milestones and associated dates will be provided in other communications.

6. Implications for Producers and Users

1. Manuals: Should be easier to read. They will be passed on to editors adept at making documentation clear for those not having English as their first language. A glossary of terms may be included with the CPF manual; one already exists in the CRD manual. Including debris or other tracking means, there is a more generic wording for several fields, e.g., satellite and station identification.

2. Sample code will be able to read both versions 1 and 2 and write version 2. This should make incompatibilities easier to manage. Conversion programs to convert version 1 to version 2 format and vice versa will be written and added to the sample code if necessary.
3. Free format headers:
    1. Users, including analysts, should be able to read version 1 or 2 of CRD or CPF.
    2. CPF producers should produce version 1 and 2 fixed format headers for the next couple years, or until stations have converted to the new format.
    3. This change requires little work for those using the new version of CPF and CRD sample code.
4. Software and meteorological sensor configuration records (C5 and C6) should be included, but should not generate error messages from the Data OCs for some time.
5. Prediction file record (H5) should be included, but should not generate error messages from the OCs for some time.
6. The Compatibility Record (60) is no longer needed or used. It should be eliminated, and a warning should be issued by the OCs if it is present.